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NOISE ABATEMENT TECHNOLOGY OPTIONS FOR CONVENTIONAL TURBOPROP AIRPLANES

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16. Abstract

The practical application of noise control technology to new and derivative conventional turboprop airplanes likely to come into service in the 1980's has been analyzed with a view to determining noise control cost/benefits. The analysis identifies feasible noise control methods, applies them to four study airplanes, and presents the noise reductions in terms of the equivalent perceived noise level at takeoff, sideline and approach locations, and the effect on the area within selected EPNL contours. Noise reductions of up to 8.3 dB for takeoff and 10.7 dB for approach are calculated for the study airplanes but, for most cases, the changes are less than 5 dB. Weight and cost increases associated with the noise control treatments are determined under the assumption that there are no changes to airplane performance or fuel consumption.

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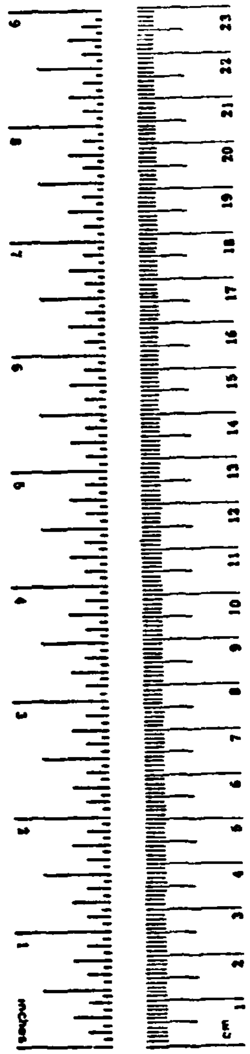
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

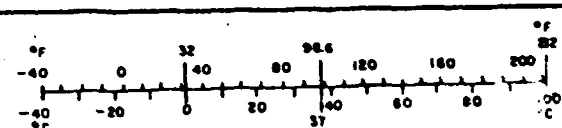
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1.0 SUMMARY

The practical application of noise control technology to new and derivative conventional turboprop airplanes likely to come into service during the decade 1980 to 1989 has been analyzed with a view to determining the potential for noise control. The purpose of the analysis was to

(a) Identify noise control methods which are applicable to conventional turboprop airplanes;

(b) Estimate the noise reductions which can be achieved by the application of noise control technology to four representative aircraft designs, in terms of the decrease in noise level under certification conditions, and the area enclosed by fixed values of effective perceived noise level;

(c) Quantify the effects of the application of the feasible noise control measures on aircraft performance and costs in order to assess the relationship between noise control benefits and cost.

Detailed results of the analysis are presented in this report, with the results summarized here.

1.1 Technology Identification

The current state-of-the-art of noise control technology as applied to conventional turboprop aircraft has been examined in terms of aircraft in service in the 1970's and recent research and development advances. The review of in-service aircraft included installations with Pratt and Whitney PT6, Rolls Royce Dart, and Allison 501 engines. These installations cover wide ranges of engine power and propeller rotational speed.

Recent increases in interest in propeller noise generation and reduction have resulted in a number of research and development studies. Results from these investigations were reviewed with a view to determining noise reduction methods which could be applied to study aircraft. Propeller noise control approaches considered were:

Reduction of Tip Mach Number
Change of Airfoil Section
Reduction of Propeller Diameter
Increase in Number of Blades
Reduction of Blade Loading
Blade Sweep
Change of Tip Shape
Irregular Blade Spacing
Ducted Propellers

1.2 Application of Noise Control To Study Aircraft

Four study aircraft were selected for analysis to determine the potential noise reductions likely to be achieved with

available technology. The aircraft consisted of two new and two derivative aircraft likely to be developed for use in the 1980's. The study aircraft had the following general characteristics:

Airplane 1: A new 6-seat, single-engined, pressurized airplane suitable for owner-flown business use.

Airplane 2: A new design, 28-passenger, twin-engined, pressurized transport-category airplane for short-haul commuter airlines.

Airplane 3: A derivative design, 30-passenger, twin-engined, pressurized transport category airplane suitable for local service airlines.

Airplane 4: A derivative design, 11,340 kg (25,000 lbs) payload, twin-engined transport category airplane primarily suited to cargo service.

Baseline noise characteristics for the new aircraft were assumed to be appropriate to noise control technology of the late 1970's. In the case of derivative aircraft, the noise control technology was assumed appropriate to the development stages of the original aircraft from which the study aircraft were derived.

Airplanes 1 and 2 have baseline sound levels with effective perceived noise level (EPNL) values which are 7 to 13 dB below the Stage 3 noise limts, Airplane 3 has baseline sound levels that comply with Stage 2 noise limits, and Airplane 4 has

baseline sound levels that can comply with Stage 3 limits if a power cutback is used and tradeoffs are made between the small exceedances at takeoff and cutback, and the margin at approach. Airplane 1 complies with FAR Part 36, Appendix F, noise limits with a margin of several decibels.

Noise reductions achievable by the application of different noise control methods, singly or in combination, were calculated for the four study airplanes. A total of 9 different combinations of noise control methods were evaluated for Airplane 1, 5 combinations for Airplane 2, and 8 combinations each for Airplane 3 and Airplane 4. The benefits due to the noise reduction methods have been assessed in terms of the reductions in EPNL for takeoff, cutback and approach powers, and the area enclosed within different EPNL contours. The associated reduction in maximum A-weighted sound level during a 305 m (1000 ft) flyover at maximum rated power can be deduced for Airplane 1 from the corresponding changes in EPNL at takeoff position

The main results of the analysis are:

1. In general, the noise control methods either singly, or in combination, provide noise reductions of less than 5 dB relative to the baseline airplanes. The exceptions are Airplanes 1 and 3 at takeoff when the largest reductions in propeller revolution rate are introduced, and Airplane 3 at approach when inlet lining treatment is installed. The maximum noise reductions achieved for the four study airplanes are:

Airplane	Maximum Reduction in EPNL (dB) Takeoff	Approach
1	8.2	4.8
2	3.3	4.4
3	6.3	10.7
4	3.3	2.0

Noise reductions for Airplane 2 are relatively small because the baseline airplane incorporates many of the available noise control measures. Airplane 4 shows relatively small noise reductions because there is little scope for further noise control.

2. Areas within the 85 EPNL contour were reduced by amounts ranging from 47% to 91% of the baseline values. The areas for baseline and maximum noise reduction cases are:

Airplane	Area Enclosed by 85 EPNL - Sq. Miles Baseline	Max. Noise Reduction
1	0.69	0.06
2	1.86	0.91
3	15.05	2.58
4	20.30	10.80

1.3 Cost and Performance Effects

Costs for each combination of noise control measures were evaluated in terms of acquisition costs and costs attributable to increase in direct operating costs when weight was added.

It was assumed that none of the noise control methods considered in the study increased fuel consumption or decreased propeller performance. The changes were considered as increases in empty weight of an airplane or, in some cases, solely as increases in acquisition cost. The increases in acquisition cost were expressed in terms of the incremental increase in net present value. Increases in operating costs for Airplanes 2, 3 and 4 are considered as a continuing cost over the life of the airplanes.

Maximum increase in weight and cost for the four study airplane were:

Airplane	Weight Increment kg (lb)	Net Present Value Acquisition Cost (1000 dollars)	Increase in Direct Operating Cost - Percent
1	18 (40)	2.5	-
2	103 (226)	9.9	1.61
3	148 (330)	14.9	2.06
4	122 (320)	17.8	0.53

1.4 Cost/Benefit Relationships

Since it is assumed in the analysis that the noise control methods do not affect airplane performance, fuel consumption remains unchanged. Thus there are two factors which can be used in assessing the cost/benefit relationships. From the aircraft operator's point of view, the combination of noise control methods that maximizes the noise reduction at minimum cost is the most cost effective approach. The second factor is the value to a community in achieving maximum noise reduction, irrespective of the cost to the operator.

While it is easy to identify the noise control approach for each study airplane which provides the greatest reduction in noise level, optimizing noise reduction and cost is more difficult. However, in all cases reductions of 30% to 40% in area for 85 EPNL can be achieved for less than 50% of the cost associated with maximum noise reduction.

It is not possible to select one particular noise control method which has the greatest impact on all four study aircraft, since the airplanes have different baseline acoustic characteristics. In some cases reduced propeller rotation rate is most important, but in other cases, inlet noise control produces the most significant noise reduction.

1.5 Stage 3 Noise Limits

The results of the noise reduction study can be interpreted in terms of Stage 3 noise limits. Considering first aircraft in the weight range of 22,680 kg (50,000 lb) and above, a reduction of Stage 3 limits does not appear to be technically feasible or economically reasonable for any aircraft likely to enter service in the 1980-89 decade.

In contrast, at low weights the introduction of new engines and new propeller technology could allow the Stage 3 limits to be reduced, perhaps by replacement of the plateau with a gradually decreasing noise limit as weight decreases.

2.0 INTRODUCTION

The provisions of Section 611 of the Federal Aviation Act of 1958 and its subsequent amendment by the Noise Control Act of 1972 direct the Federal Aviation Administration to promulgate noise regulations for aircraft. These regulations, which may not compromise safety, must also meet the tests of economic reasonableness, technological practicality and appropriateness to the classes of aircraft to which they are applied. In implementing the statutes FAA has stated that it has a continuing requirement to produce regulations that will insure the lowest reasonable noise levels from aircraft when it is economically reasonable to apply "available noise reduction techniques."

In order to fulfill its mandate, FAA must be able to anticipate the scientific state of developments in noise control technology, the timing of translation of such technology into flight certifiable hardware, and the cost/benefit relationships for the introduction of these improvements. These factors must all be balanced in such a way that the test of economic reasonableness can be met, realizing the often conflicting views of a public demanding lower noise levels as quickly as possible, and the time-dependent ability of the overall aircraft industry to absorb costs.

The aircraft industry is moving into the decade of the 1980's with a resurgence of interest in turboprop aircraft. The soaring cost of fuel has not only triggered the NASA research program to explore the Mach 0.8 cruise turboprop, but of more immediate significance for the 1980's, generated a demand for new and derivative type designs of more conventional turboprop

airplanes. The airline deregulation act has resulted in the removal of trunk air carrier service with turbojet airplanes from many communities, with numerous commuter airlines coming in to fill the demand for service. The lower initial cost, fuel efficiency, lower noise levels, with performance capabilities more nearly matched to short haul service, make the conventional turboprop aircraft, even with their lower cruise speeds, most suitable for local service routes. In the 1977 Census of Civil Aircraft 335 turboprops were listed in air carrier use in the United States; by mid-1979 the Air World Airline Fleet Summary showed 563 turboprops in use by air carriers.

The renewed interest in turboprops will be met with both new aircraft type designs and with airplanes that are derivatives of existing type designs. This report provides an analysis of the noise control technology that is likely to apply to these airplanes that are put into service during the decade from 1980 to 1989. The state of noise control technology represented by aircraft in service in 1979 is described in Section 3. A technology assessment of noise control measures applicable to turboprop aircraft and their use in contemporary designs is discussed in Section 4. The ability of current technology to minimize the noise signatures of two new and two derivative airplanes is analyzed in Section 5.

Benefits of various noise control measures are assessed in Section 5 in terms of the area enclosed within contours of constant effective perceived noise level (EPNL) and in terms of reductions in EPNL at locations used for noise certification by FAR Part 36. Costs introduced by the various noise control measures are discussed in Section 6. Benefits and

costs are examined in terms of changes to the baseline airplane configurations.

3.0 CURRENT STATE-OF-THE-ART

3.1 Introduction

In contrast to the history of development of turbojet and turbofan engines in which major reductions in noise have been made over the last 15 years, turboprop power plants for conventional airplanes, with a few notable exceptions, have remained largely unchanged for more than two decades. In fact, in the higher horsepower ranges, current production engines are more highly developed, larger horsepower versions of engines that went into production over 25 years ago; their designs remain basically unchanged today.

More than 95 percent of the civil turboprop fleet is propelled by various versions of but four basic engine series, Pratt and Whitney-Canada PT6, AiResearch TPE 331, Rolls-Royce Dart, and Allison 501. Each series has a unique design concept, resulting in different power management procedures, and consequent noise characteristics. Only the PT6 and TPE 331 series have overlap in their horsepower ranges, and can thus be competitive in application. The basic characteristics that affect the noise characteristics of these four engine series are listed in Table 1.

The predominant source of noise for almost all existing turboprop airplanes is propeller noise. The wide range of propeller helical Mach numbers, 0.57 to 0.85, which controls to a large extent propeller noise, and the noise characteristics associated with the particular mechanical designs of the different engine series, produce strikingly different noise spectra for different turboprop airplanes. This contrasts

TABLE 1

GENERAL CHARACTERISTICS OF TURBOSHAFT ENGINE SERIES

	P&W-C PT6	AiResearch TPE 331	Rolls-Royce Dart	Allison 501
Power kW (hp)	336-835 (450-1120)	298-701 (400-940)	1298-2420 (1740-3245)	3132-3490 (4200-4680)
Compressor*	AC	C	C	A
Max prop rpm	1210-2200	1591-2000	1163-1395	1020
rpm variable (V) or fixed (F)	V	F	V	F
Prop diameter m (ft)	2.19-3.43 (7.17-11.25)	2.26-2.74 (7.4-9)	3.66 (12)	4.12 (13.5)
No. of blades	3-5	3-4	4	4
Typical helical Mach No. at V_2+10	0.66-0.82	0.64-0.82	0.80	0.68
Year in service	1963	1965	1955	1952

* A - Axial
C - Centrifugal

with the generally similar noise characteristics of turbofan engines of contemporary design.

The substantial differences between different turboprop installations can be seen by comparing EPNL values measured during noise certification conditions for different airplanes, with EPNL values computed from a multiple regression equation calculated from the measured EPNL values for the entire set of airplanes. The regression equation is

$$L_{EPN} = 10\log_{10}(NxP) + 47.82\log_{10} M_h + 21.2\log_{10}\frac{V}{h} + 81.8 \quad (1)$$

where N is number of engines
P is average horsepower per engine
M_h is helical tip Mach number
V is true airspeed in knots
h is height in feet

This equation has a multiple correlation coefficient of 0.838 and a standard error of 3.2 decibels. The difference between measured EPNL and that calculated from the above equation can be large. These differences are listed for different airplane types in Table 2.

Since each of the different turboprop engines series now in production is likely to be used in new and derivative airplanes that can be expected to appear in the 1980's, the characteristics of the predominantly different existing engine/propeller installations are examined in the following sections. The PT6 series is used as representative of the

TABLE 2

DIFFERENCE BETWEEN MEASURED EPNL AND EPNL CALCULATED FROM EQUATION 1

Airplane	Operation	Measured Minus Calculated EPNL
Nord 262	T/O	0
"	Approach	2.3
Mohawk 298	T/O	-0.8
"	Approach	2.5
H-S 748	T/O	1.5
"	T/o Cutback	0
"	Approach	9.5
Lockheed L-382	T/O	4.1
"	Approach	-3.4
DeHavilland DHC-7	T/O	-7.0
"	Approach	4.0
Shorts SD 330	T/O	0.5
"	T/O Cutback	-0.4
"	Approach	0.3

lower horsepower ranges and is particularly interesting because it has such a variety of different installations. The Dart and Allison 501 series are essentially the only engines available in their horsepower ranges and, thus, deserve attention of themselves. The TPE 331 series is not examined separately, since most of the noise reduction techniques applicable to the PT6 series will also apply to the TPE331 series.

3.2 Characteristics of PT6 Installations

Early versions of the PT6, in service since 1963, were originally used in twin-engined airplanes of less than 5670 kg (12,500 lb) maximum weight. The most prolific examples are the Beech King Air 90 and Beech 99, which between them constituted 40 percent of the domestic turboprop fleet in 1977. A typical early installation has 410 kW (550 hp) per engine, propeller rpm at takeoff power is 2200, and a three-bladed propeller has a helical tip Mach number of 0.791 at best rate-of-climb speed V_y. In later models, as power was increased to 537 kW (720 hp), rpm was retained at 2200, and 4 blades were used on the propeller, keeping the helical Mach number essentially the same at 0.793.

Introduction of the King Air A200 model with engines increased to 634 kW (850 hp) was accomplished by an rpm reduction to 2000; however, an increase in propeller diameter kept the helical Mach number at 0.788. The change in power from 410 to 634 kW (550 to 850 hp) was thus accomplished by propeller and rpm changes that kept helical Mach number and noise characteristics essentially constant.

One feature of the PT6 series that can be used for noise control is that propeller rpm, as well as torque, can be

varied below maximum rated rpm, at pilot option. Thus, noise abatement procedures such as reduced rpm climb can be used. This feature differs from the TPE 331 series where propeller rpm in flight is essentially kept constant (varying from 96 percent at cruise to 100 percent for takeoff and landing), with variation in torque being controlled by a "power level" that adjusts fuel flow.

Of interest for noise control in airplanes for the 1980's are the two recent versions of the PT6 series, each rated at 835 kW (1120 hp) but using quite different propeller installations. The two-engined Shorts SD330 uses a 5-bladed propeller of 2.82 m (9.25 ft) diameter, turning at 1675 rpm, with a helical tip Mach number of 0.751 at takeoff climb. The four-engined DeHavilland DHC-7 uses a 4-bladed propeller of 3.43 m (11.25 ft) diameter, turning at 1120 rpm, with a helical tip Mach number of 0.655 during takeoff climb. At the same height, the EPNL for the DHC-7 is 7.4 decibels per engine lower than for the SD330.

Much of this difference is due to two factors associated with the differences in propeller installation. The slower turning 4-bladed propeller on the DHC-7 has a fundamental blade passage frequency of 81 Hz, while the faster turning 5-bladed propeller on the SD330 has a fundamental frequency of 140 Hz. The higher Mach number of the SD330 also provides somewhat greater sound levels at the fundamental frequency and at higher harmonics. Perceived noise level frequency weighting function, which causes higher frequencies to be more accentuated than lower frequencies, increases the PNL difference between the two airplanes.

These technical features that affect EPNL and the ability to apply various noise control features to turboprop airplanes are discussed in detail in Section 4 of this report.

Comparisons between the noise spectra of the two airplanes can be seen in Figures 1a and 1b, which show the one-third octave sound pressure levels at the time the maximum tone-corrected perceived noise level (PNLTM) occurs in level flyovers at takeoff power, and in Figures 2a and 2b, which show narrowband (4 Hz constant bandwidth) analyses for the same signals. Both the one-third octave and narrowband spectra clearly display the dominant role of the sound pressure levels at the first few harmonic frequencies of the propeller blade-passage rate in controlling the noise signatures of these airplanes.

3.3 Characteristics of a Rolls-Royce Dart Installation

The Dart engine has evolved from a design started in 1945 through a series of engines with different model and "Mark" numbers covering engines delivering from 1298 to 2420 kW (1740 to 3245 hp). Airplanes in service in the United States that use various versions of the Dart include the Fokker F-27 series, Gulfstream I, Hawker-Siddeley 748, Nihon YS-11, and Convair 600 series conversions. Since the Dart is almost exclusively the only turboprop engine available in the 1500 to 2240 kW (2000 to 3000 hp) range, it is the most likely engine for use in future twin-engined airplanes of 18,000 to 27,000 kg (40,000 to 60,000 lb) takeoff weight, which generally have power loadings between 5 and 6 gm/W (8 and 10 lb/hp). Thus, this engine series, which has been in service for over 25 years, is likely to continue for many more years.

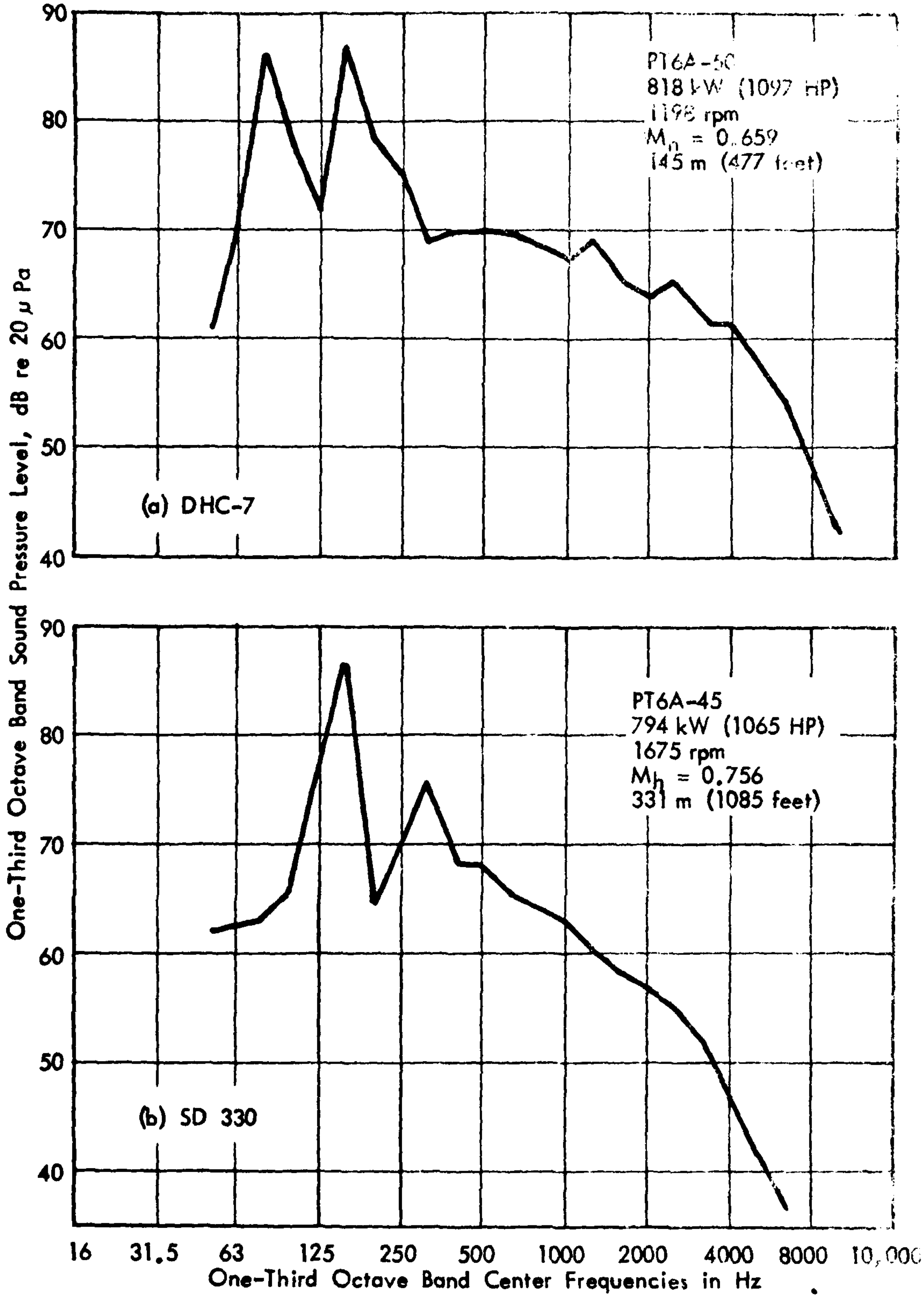


FIGURE 1. ONE-THIRD OCTAVE BAND SOUND PRESSURE LEVELS FOR SD330 AND DHC-7 AT TIME OF PNLTM (TAKEOFF POWER)

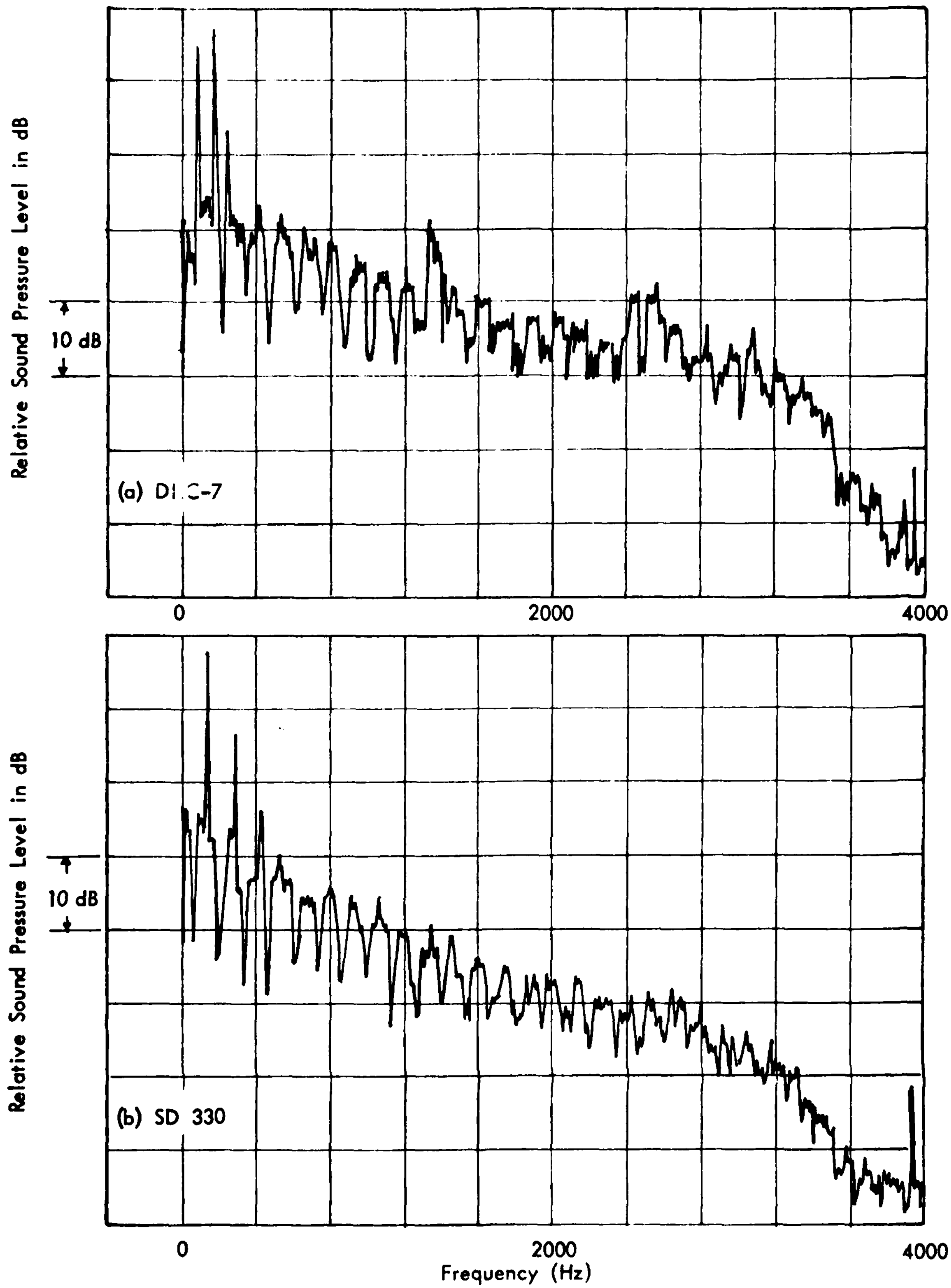


FIGURE 2. CONSTANT BANDWIDTH (4 Hz) SOUND PRESSURE SPECTRA FOR SD330 AND DHC-7 AT TIME OF PNLTM (TAKEOFF POWER)

The Dart 532-2L installation in the Hawker-Siddeley 748 Series 2A airplane is representative of contemporary versions of the Dart. In this version, the Dart develops a maximum of 1827 kW (2450 hp), using a gear ratio of 0.093:1 to drive a 3.66 m (12 ft) diameter, 4-bladed propeller at 1395 rpm, with a helical tip Mach number of 0.80 during takeoff climb.

The combination of high helical tip Mach number and high horsepower generates high sound pressure level tonal components at the fundamental frequency of 93 Hz and numerous of its harmonics. These contributions to the acoustical spectrum are strongly evident in the one-third octave SPL spectra shown in Figure 3. The spectra in Figure 3 labeled as A and B are for takeoff and climb powers 1650 and 1245 kW (2213 and 1670 hp), respectively, with tip Mach numbers of 0.805 and 0.702 at the time of PNLTM during level flyovers.

The strong dependence of propeller noise on tip Mach number and horsepower can be seen by comparing spectrum C on Figure 3 with spectra A and B. Spectrum C is for an approach power setting of 480 kW (644 hp) and a tip Mach number of 0.655. The high level of the second harmonic drops drastically as power and Mach number are reduced--more than 20 decibels from takeoff to approach power--while the levels associated with the higher harmonics are reduced by 10 to 15 decibels. The spectrum for approach power is also shifted one-third octave lower in frequency since the propeller rpm has been reduced by 25 percent. (Note that the relative SPLs at the fundamental and second harmonic frequencies are distorted by cancellation and reflection effects at the ground surface due to the finite height microphone used in noise certification measurements.)

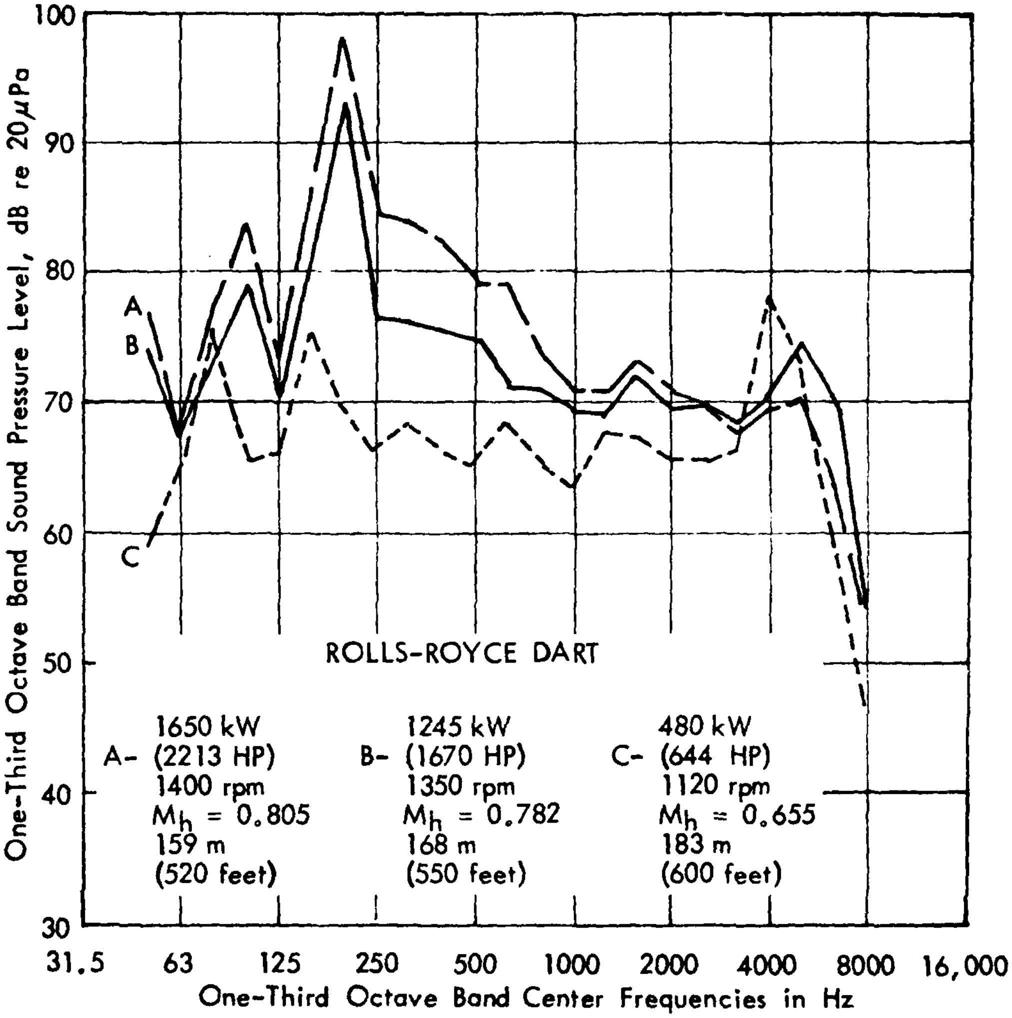


FIGURE 3. ONE-THIRD OCTAVE BAND SOUND PRESSURE LEVELS FOR HS 748 AT TIME OF PNLTM (VARIOUS POWERS)

Two other characteristics of the Dart are also apparent in the spectra on Figure 3. At low power, the centrifugal compressor radiates strong tonal components in the 4000 to 5000 Hz range. As power is increased, the compressor tones decrease in level although they are still apparent even at takeoff power. Further, there are numerous other tonal components in the spectra--for example, around 1600 Hz--that cannot be identified with propeller harmonics or the compressor. These tones are obviously associated with other mechanical features of the engine, although we have not been able to associate them with gear frequencies.

The pronounced tonal composition of the Dart spectra is further demonstrated in Figures 4a and 4b. A narrowband analysis (4 Hz constant bandwidth, 0-4000 Hz) of the takeoff power spectrum (spectrum A on Figure 3) is shown on Figure 4a. The first nine propeller harmonics are clearly distinguishable, as well as other unidentified tones in the 1600 or 2400 Hz ranges. A narrowband (10 Hz constant bandwidth, 0 to 10,000 Hz) analysis of the approach power spectrum (spectrum C on Figure 3) is shown on Figure 4b. In addition to propeller tones and the unidentified mechanical noise at 1330 Hz, the compressor tone structure in the 4000 to 5000 Hz range is clearly apparent.

3.4 Characteristics of an Allison 501 Installation

The 501 series of Allison engines are the civil versions of the military T56 series of engines. This line of 3132 to 3729 kW (4200 to 5000 hp) engines has been in service since 1952 and continues to be produced today. Civil use of the engines

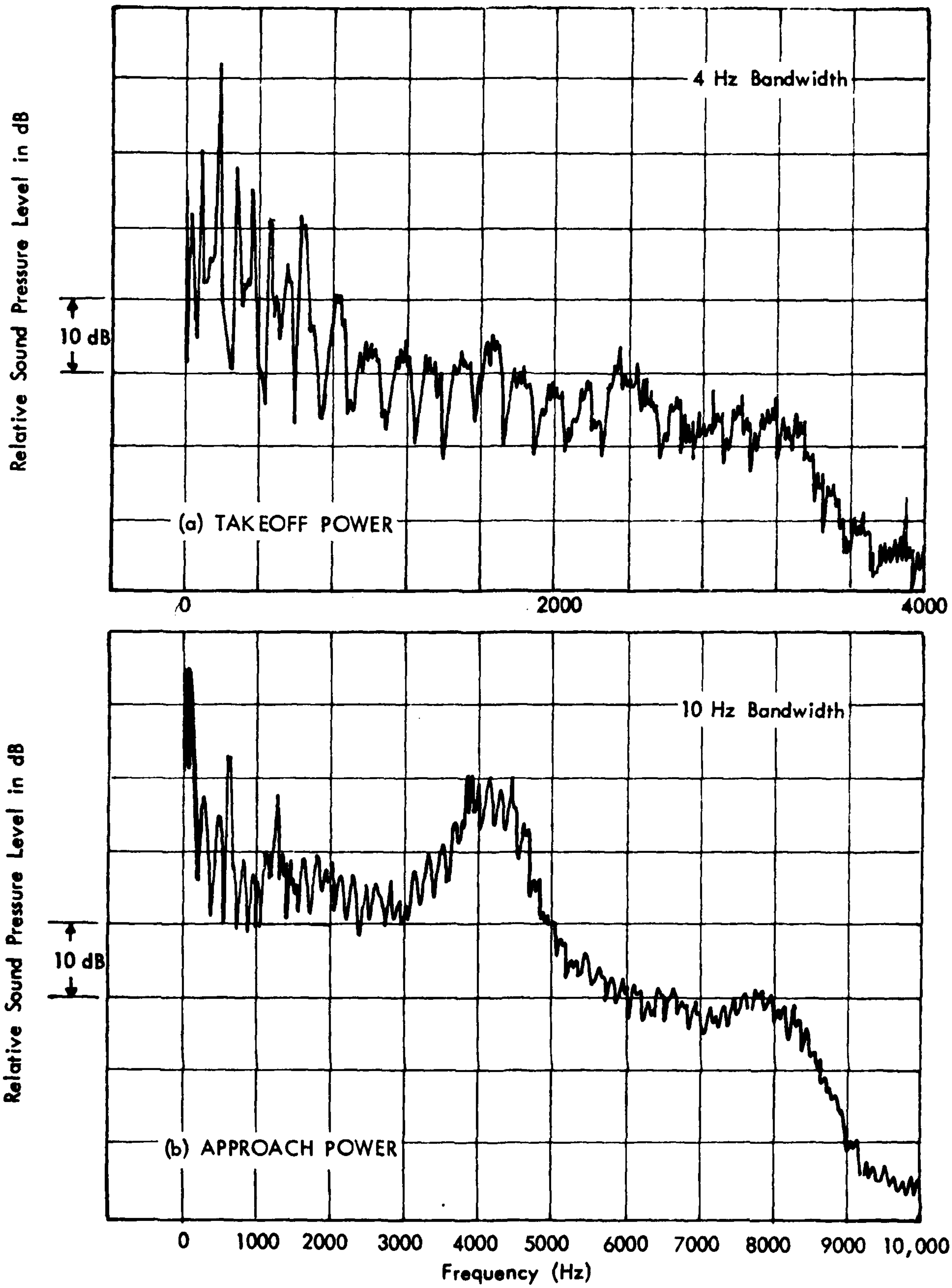


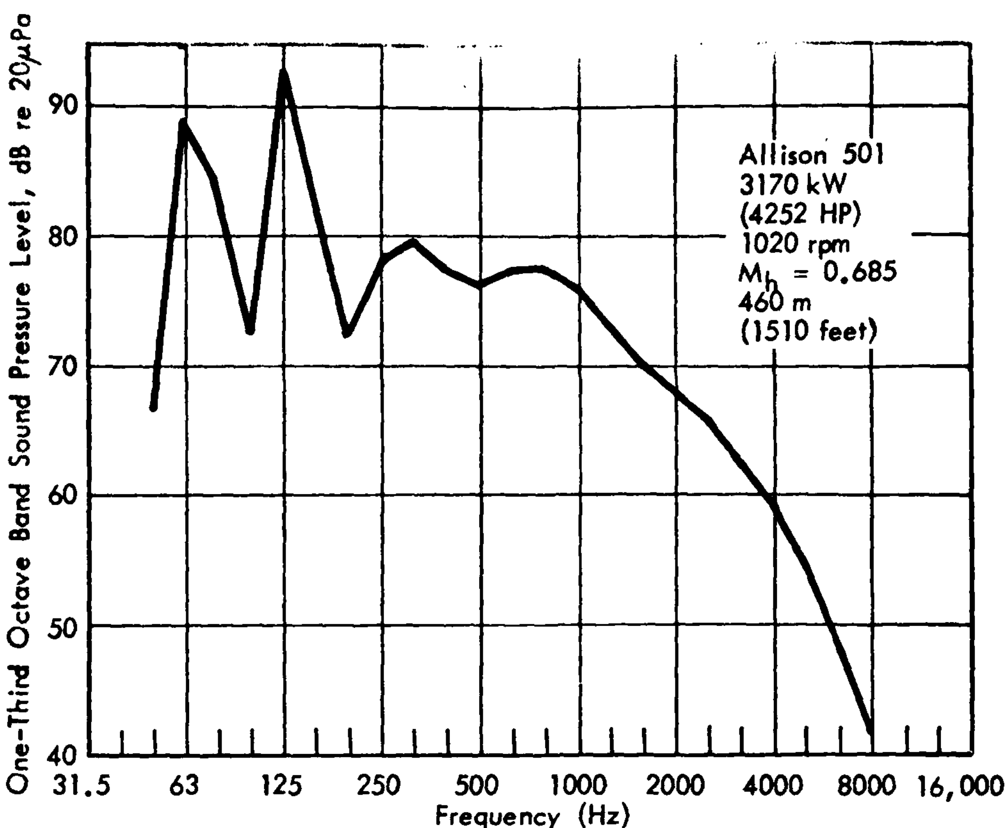
FIGURE 4. CONSTANT BANDWIDTH NOISE SPECTRA FOR HS 748 AT TIME OF PNLTM

primarily on the Convair 580, Lockheed Electra L-188, and the civil version of the Lockheed Hercules, the L-382. A twin-engined airplane of 80,000 to 100,000 pounds takeoff weight could be a suitable new airplane using these engines.

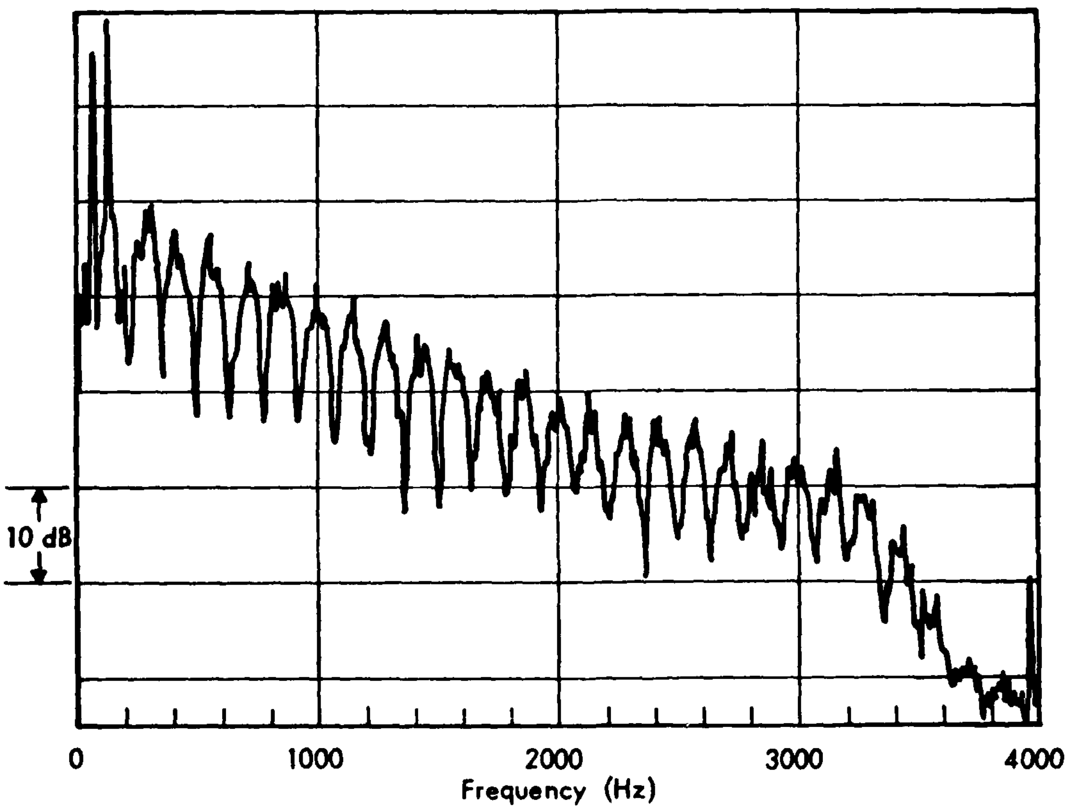
The 501-D22 installation in the Hercules is representative of current airplanes. In this use the engine develops approximately 3132 kW (4200 shaft hp) at takeoff, driving a 4.12 m (13.5 ft) diameter, 4-bladed propeller through a gear ratio of 0.074:1 for a propeller rpm of 1020. Helical tip Mach number is 0.681 at takeoff climb speed.

An interesting feature of the 501 engine series is its constant speed operation, irrespective of power setting. Power is set by adjusting engine torque. The constant propeller speed holds tip Mach number constant at any specified speed. At the high power settings used for takeoff, EPNL for this engine varies approximately as the cube of horsepower, allowing some capability for noise reduction through reduced power climb procedures.

The noise signature of the Allison engine is dominated by the SPL at the fundamental and second harmonic of the 68 Hz blade passage frequency, which are 15 to 20 decibels higher in level than any other features in the spectrum. One-third octave band SPL and narrowband (4 Hz constant band width, 0-4000 Hz) analysis of the takeoff noise spectrum at the time of PNLTM, at a height of 457 m (1500 ft) are shown in Figures 5a and 5b.



(a) One-Third Octave Band Spectrum



(b) 4-Hz Constant Bandwidth Spectrum

FIGURE 5. SOUND LEVELS FOR L-382 AT TIME OF PNLTM (TAKEOFF POWER)

4.0 PROPELLER NOISE TECHNOLOGY

Before considering potential noise control approaches for the four study aircraft it is appropriate to review the current state of propeller noise technology. The review presents propeller noise prediction methods, analytical and empirical, and identifies possible means of reducing propeller noise. Prediction methods and noise control approaches are both required in the estimation of potential noise reductions for the study aircraft.

4.1 Analytical Studies

4.1.1 General Characteristics of Propeller Noise

A typical propeller noise spectrum contains a series of tones, at the propeller blade passage frequency and multiples thereof, superimposed on a broadband background. The tone, or rotational, noise components are generated by several mechanisms and it is necessary to review briefly these mechanisms so that the important ones from the viewpoint of takeoff and landing noise can be identified.

The mechanisms generating the tones can be divided into two groups, one of which is associated with steady aerodynamic loads and the other with unsteady loads. Steady loading noise is associated with linear thickness noise, which is monopole in character, and linear lift or loading noise, which has characteristics of a dipole source. In addition there are non-linear thickness and loading noise sources which are quadrupole in character.

Unsteady and non-uniform sources of tonal noise also exist. This arises from atmospheric turbulence and from vortices from the ground or airplane fuselage. Non-uniform loading also results from blockage by the nacelle and wing when a tractor propeller is used, and from blockage by upstream structures such as the fuselage, wing and tailplane when the propeller is of the pusher type.

Experience has shown that the influence of atmospheric turbulence and vortices from the ground or fuselage are significant only during static tests. (This will be discussed later). Thus these noise sources can be neglected when considering takeoff and landing noise. Blockage by the structure will still be present, but is significant only at very low tip Mach numbers for tractor propellers. It is always significant for pusher propellers.

Non-linear thickness and loading noise becomes important only at transonic tip Mach numbers. This leaves steady loading linear thickness and lift noise as being the two items of main interest in the following discussion of tonal components.

Broadband noise results mainly from random vortex shedding by the blade trailing edge, although atmospheric turbulence may play a role. In general, the importance of broadband noise is difficult to determine in any airplane test situation because of the noise generated by airflow over the airframe. However, the broadband noise is usually assumed to have a negligible effect on the A-weighted sound level or perceived noise level of the propeller, unless the blade tip Mach number is very low.

Theoretical directivity patterns associated with the different noise sources are shown in Figure 6. Linear loading noise is shown in terms of the thrust and torque components, with the positive and negative signs indicating relative phase. The resulting loading noise for a blade element at radius r has a two-lobe directivity pattern, with the node between the lobes occurring at an angle σ, with [1]

$$\sigma = \cos^{-1}(M_x/M_r^2)$$

where M_x is the flight Mach number and M_r the blade element Mach number at radius r. The pressures in each lobe of the directivity pattern are each 90° out of phase with respect to monopole thickness noise.

It is evident from the directivity patterns shown in Figure 6 that the dominant noise mechanism may change with angle from the propeller axis. For example, thickness noise may dominate in the plane of rotation of the propeller. This factor may be important when determining the noise reduction potential of different noise control methods.

4.1.2 Analytical Studies

Early analytical studies of propeller noise considered each of the three main components separately. Gutin [2] performed the initial analysis of lift noise, Deming [3] considered thickness noise, and Yudin [4] studied vortex noise. At first the analysis of lift and thickness noise considered only static aircraft, but subsequent work, mainly by NASA (or NACA)and Hamilton Standard, extended the analyses to include forward motion and introduced other improvements. For example,

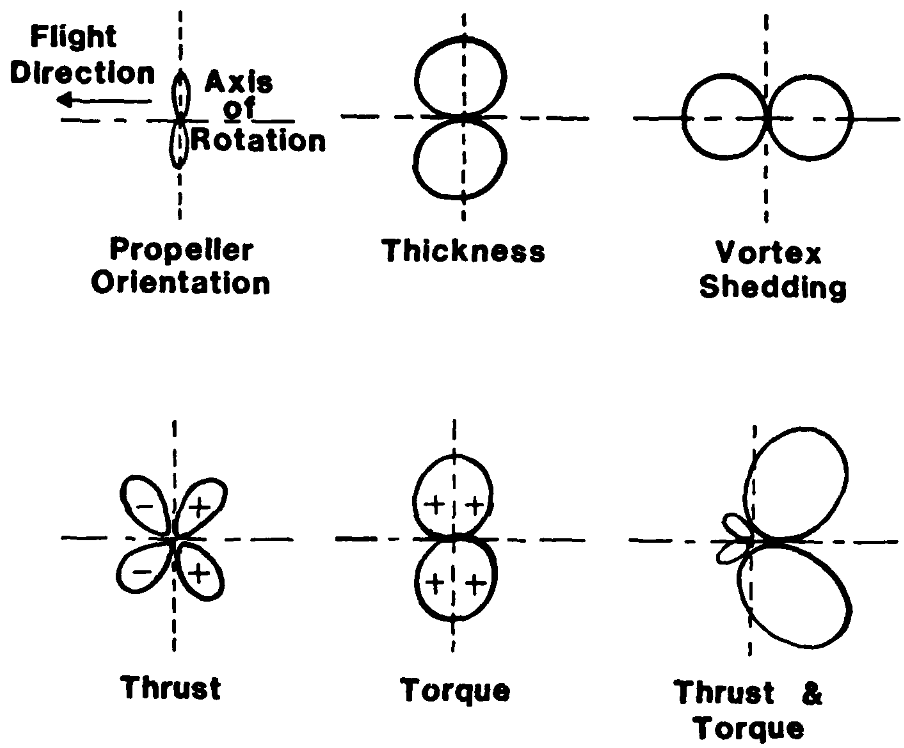


FIGURE 6. THEORETICAL DIRECTIVITY PATTERNS FOR PROPELLER NOISE COMPONENTS

Garrick and Watkins [5] extended Gutin's analysis to include forward speed and Watkins and Durling [6] extended the analysis further to show the effect of spanwise and chordwise loading distribution.

Recently, there has been increased activity in the analysis of propeller noise, and the approaches [1, 7-11] have all been based on the acoustic analogy developed by Lighthill and Ffowcs Williams. Much of the recent effort has utilized time domain analysis. This general approach has the advantage that it does not involve transcendental functions, but, on the other hand, it does require the use of high speed computers to perform the required numerical differentiation and integration.

The time domain approach has the disadvantage that it is difficult to establish the relative importance of different parameters without performing extensive calculations involving parametric variations. Results of such calculations can be found, for example, in [10] and [11]. The alternative frequency domain approach followed by Hanson [1] presents closed-form results which demonstrate the roles of blade geometry and operating conditions. The results are more general in form than those of earlier studies [2-6] in that Hanson includes the effects of non-compactness of the source, and blade sweep and offset. In terms of propeller noise generation, compact sources are those for which the motion and fluctuations of the forces on a blade are such that their acoustic effect is equivalent to that of a single point in motion. Non-compactness takes into account the fact that each element of the blade surface radiates sound at a time different from those of other elements. It is considered by some investigators that

sources of propeller noise can usually be considered as compact if the tip rotational Mach number is less than 0.7.

One of the main areas of interest in Hanson's analysis is that of the Hamilton Standard supersonic propeller or propfan which is designed to operate with supersonic tip helical Mach numbers during high speed subsonic cruise. Such propellers are not of interest to the present discussion as their introduction to commercial service is far from certain at the present time. However, the general results of Hanson's work are of interest in that they reiterate the type of results obtained in earlier analyses and provide extensions to those analyses.

Hanson [1] considers volume displacement monopole (thickness noise), drag and lift dipole, and quadrupole noise sources. The drag dipole represents a force oriented in the local convection direction and the lift dipole a force perpendicular to the convection direction. For present purposes only the thickness monopole and the dipole lift or loading noise sources will be considered. These two sources probably make the main contributions to the tonal noise components for takeoff and landing conditions.

Reproducing the results of Hanson [1] directly, the harmonic components of the pressure at radius r can be written as:

$$P_{Vm} = -\rho_o c_o^2 \frac{m^2 B^3 M_T^2 \sin\theta \; e^{i\, mB\left(\frac{\Omega_D r}{c_o} - \frac{\pi}{2}\right)}}{2\pi \frac{Y}{D} (1 - M_x \cos\theta)^3} \cdot \int_0^1 J_{mB}\left(\frac{mBz\, M_T \sin\theta}{1 - M_x \cos\theta}\right) e^{i(\phi_o + \phi_s)} \, t_b B_D^2 \psi_V(k_x)\, dz \tag{2}$$

for the mth order harmonic of thickness noise, and

$$P_{Lm} = i\rho_o c_o^2 \frac{mB^2 \sin\theta \, e^{imB\left(\frac{\Omega_D r}{c_o} - \frac{\pi}{2}\right)}}{8\pi\frac{V}{D}(1 - M_x \cos\theta)^2} \int_0^1 \frac{M_r}{z}(M_r^2 \cos\theta - M_x) \cdot$$

$$J_{mB}\, \frac{mBz\, M_r \sin\theta}{1 - M_x \cos\theta}\, e^{i(\phi_o + \phi_s)}\, C_L B_D \psi_L(k_x) dz \qquad (3)$$

for the mth harmonic of lift noise. Identification of all the variables used in Eq. (2) and (3) can be found in [1]. It is necessary in the present discussion to identify only those parameters which are of particular interest.

Source non-compactness is accounted for in Eqs. (2) and (3) by the terms $\psi_V(k_x)$ and $\psi_L(k_x)$, respectively. Calculations performed by Hanson [1] for typical takeoff conditions of a large conventional propeller airplane, and flyover conditions of a general aviation airplane indicate that non-compactness effects reduce the predicted thickness noise by 3 to 6 dB at the lower order harmonics and the loading noise by 0 to 3 dB. In this case lower order harmonics are those for which mB is less than 20, approximately, where B is the number of blades and m the harmonic order.

Sweep and offset of the propeller blade are represented respectively by the phase lag terms ϕ_s and ϕ_o. For a straight blade $\phi_s = 0 = \phi_o$, a condition which is true for all current general aviation and large conventional propellers. The terms are important, however, if the noise reduction potential of blade sweep is to be estimated.

For conventional propellers the main items of interest in Eqs. (2) and (3) are the roles played by propeller geometric parameters:

B = number of blades
D = propeller diameter
C_L = blade lift coefficient
B_D = ratio of chord to diameter = b/D
t_b = ratio of maximum thickness to chord = t_{max}/b

and by operational parameters

M_T = tip rotational Mach number
M_x = flight Mach number
M_r = section relative Mach number = $\sqrt{M_x^2 + z^2 M_T^2}$
$\Omega_D = \Omega/(1 - M_x \cos \theta)$

where z = normalized radial coordinate = r_o/r_T.

and $\Omega = 2\pi$ times shaft rotational frequency.

Obviously, care has to be taken in interpreting the influence of the above parameters, because changes to them will have implications not only in terms of the radiated noise but also the aerodynamic performance. For example, the equations show that for a given value of (mB) the propeller with the lower number of blades, and hence the higher value for m, will generate the lower noise level. However, the propeller with the greater number of blades may well operate at a lower tip Mach number.

One parameter which is of particular interest is the blade tip Mach number since it has been recognized, both analytically and experimentally, that it is the most important parameter with regards to noise control. In Eqs. (2) and (3) the tip Mach number appears in the form of tip rotational Mach number

$$M_T = \frac{\Omega r_T}{c_o} ,$$

where Ω is the propeller rotational frequency and r_T the radius of the blade tip, blade element helical Mach number M_r (defined earlier), and flight Mach number M_x. In the case of thickness noise, the helical Mach number appears only through the parameters ϕ_s and ϕ_o. Since these parameters are zero for a straight blade, helical Mach number as such does not play a role in the prediction of thickness noise by Eq. (2).

Inspection of Eqs. (2) and (3) shows that, with the exception of the Bessel function, the predicted effect of M_T, M_r or M_x is the same for all harmonics. Consequently, any harmonic dependent variation must be contained within the Bessel function term. The Bessel function can be written in the form:

$$\begin{aligned} J_{mB} \frac{mBzM_T \sin\theta}{1 - M_x \cos\theta} &\equiv J_{mB}\,(2ZM_T) \\ &= (ZM_T)^{mB} \sum_{k=0}^{\infty} \frac{(-1)^k (ZM_T)^{2k}}{k!\,(mB+k)!} \\ &= \frac{1}{(mB)!}\,(ZM_T)^{mB} \left\{ 1 - \frac{(ZM_T)^2}{mB+1} + \frac{(ZM_T)^4 + \cdot\cdot}{2(mB+1)(mB+2)} \right\} \end{aligned} \tag{4}$$

The term M_T^{mB} will cause a rapid increase in harmonic pressure at the higher order harmonics as M_T increases. The net rate of increase in pressure of any given harmonic will be lower, however, because of the offsetting effect of the negative terms such as the second term shown in Eq. (4). The high rate of increase in sound pressure of the higher order harmonics is of particular importance when considering A-weighted sound levels or perceived noise level, as will be discussed later in Section 4.2.2.

4.2 Experimental Studies

4.2.1 Flight Effects

Early experimental studies of propeller noise were based on static tests. Subsequently, in about 1970, it became apparent that static and flight test results were significantly different in terms of harmonic content. The effect is demonstrated in Figure 7 which contains narrowband spectra for a de Havilland Canada DHC-6 Twin Otter airplane [12]. It is seen that, although there may be little change in the levels of the two or three lowest order harmonics, the higher order harmonics show a dramatic reduction in sound level due to the forward motion.

The difference in noise levels between static and flight conditions can be attributed to differences in the in-flow turbulence (Figure 8). Atmospheric turbulent eddies ingested by the propeller during static testing are elongated and chopped by the propeller blade. This chopping results in high levels of the harmonic noise components. In contrast the inflow contraction ratio in flight is much smaller and the

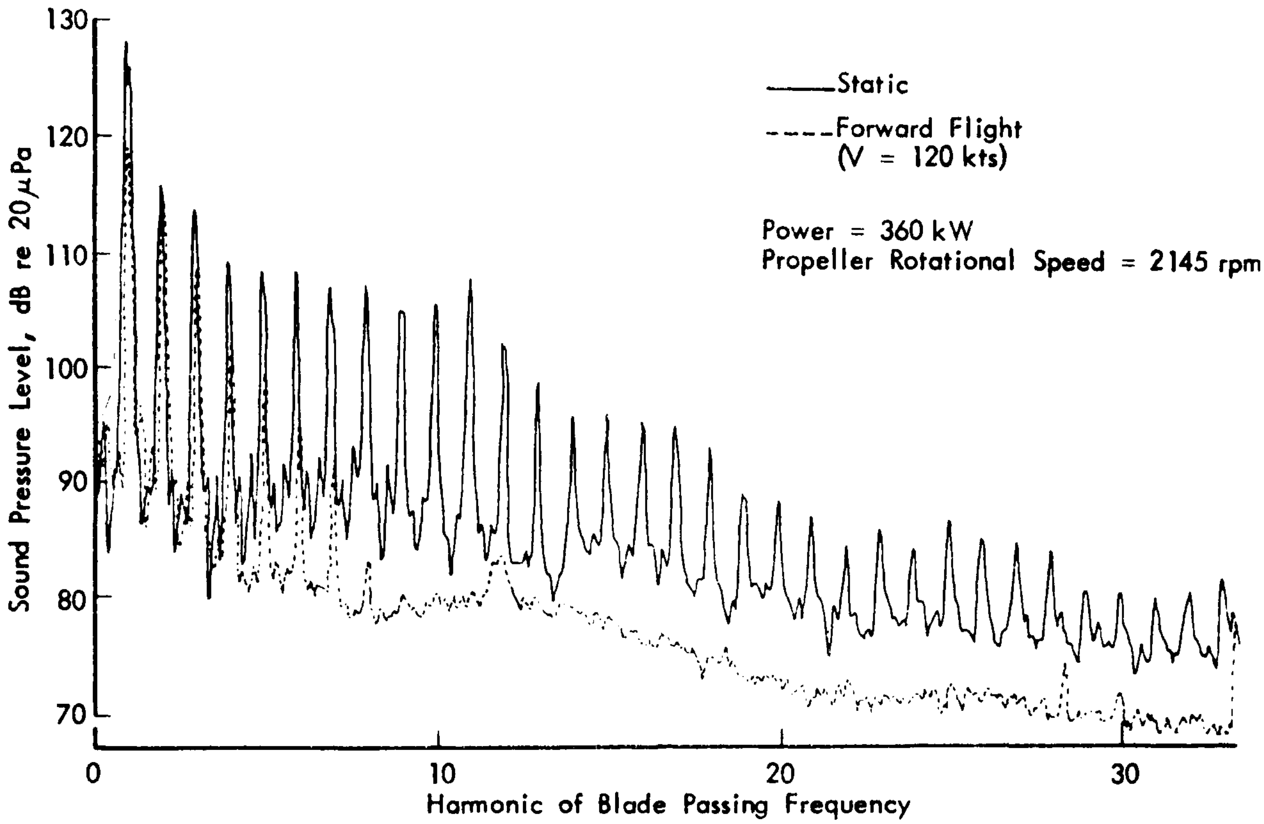


FIGURE 7. COMPARISON OF PROPELLER NOISE SPECTRA FOR STATIC AND FORWARD FLIGHT CONDITIONS [12]

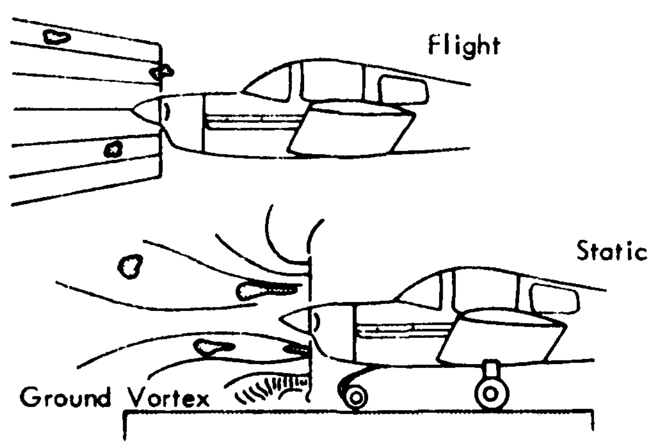


FIGURE 8. PROPELLER INFLOW TURBULENCE AS DEPICTED IN [12]

eddies are not elongated. The tone-like noise components are thus much lower. Additional noise under static test conditions may also result from the presence of vortices from the ground and surrounding structures.

One result of the discovery of the important difference between static and flight test data has been the necessity to regard earlier static test results with a certain amount of caution. Early analytical analyses, which did not account for the unsteady or non-uniform loads imposed by inflow turbulence and vortices, were applicable to flight conditions with low inflow turbulence, but account has to be taken of inflow irregularities when analytical models are to be used for static conditions.

4.2.2 Flight Test Data

Several flight test programs have been conducted recently with the objective of obtaining empirical relationships between far field noise levels, particularly A-weighted levels, and propeller geometry or operational conditions. Two such test programs [13,14] have been discussed briefly in [15], but it is appropriate to present some of the results again in this section. A more recent test program by Heller et al has been reported in [16].

Results from the three programs for general aviation aircraft show some disagreement regarding the influence of propeller power, P, on the A-weighted sound level. Galloway [13] measured the noise levels of two single-engined airplanes, each with a two-bladed propeller. In one case the propeller was fixed-pitch and in the other variable-pitch. For tip Mach

numbers above 0.75, Galloway found the A-weighted sound level was independent of propeller power. Rathgeber and Sipes [14], using data for a range of unidentified Cessna single and twin-engined aircraft, indicate that the A-weighted sound level varies as 20 log P, and Heller et al [16] obtain a 15 log P dependence. The range of tip Mach numbers tested by Rathgeber and Sipes (0.75 to 0.95) is similar to that of Galloway's tests (0.71 to 0.89) but that for the tests of Heller et al is somewhat lower (0.66 to 0.81). The procedure followed by Heller et al in determining the relationship between sound level and engine power is not identified and, since the engine power follows an approximate linear relationship with tip Mach number (Figure 9) it would appear that engine power and tip Mach number could be interchangeable.

Empirical relationships between blade tip Mach number and overall A-weighted sound level have been developed from the data in [13] and [14]. In addition Heller et al [16] developed relationships between tip Mach number and the A-weighted levels of the harmonic components. In all cases tip helical Mach number was used as the variable, although the numerical value was little different from that of the tip rotational Mach number. Equations (2) and (3) suggest that the latter variable may have been the more appropriate one to choose.

It has been shown in [15] that the data measured by Galloway for level flyovers at an altitude of 305m (1000 ft.) follow a linear regression line whose equation is given by

$$L_{Amax} = 96.3 + 240 \log_{10} M_h \quad \text{dB} \qquad (5)$$

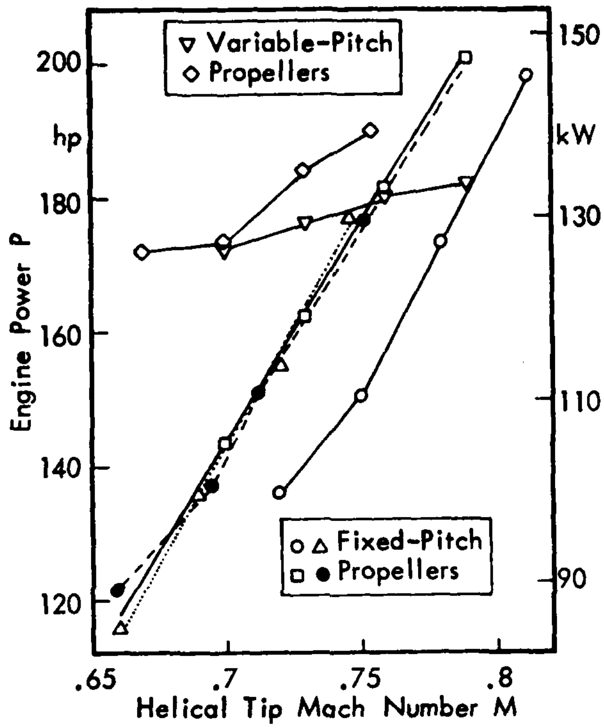


FIGURE 9. VARIATION OF ENGINE POWER WITH PROPELLER TIP MACH NUMBER FOR TEST PROPELLERS [16]

where L_{Amax} is the peak overall A-weighted sound level, and M_h is the tip helical Mach number. The data and regression line are shown in Figure 10. In addition, if the data in [14] are adjusted to remove the assumed dependence on engine power, it is found (Figure 11) that the regression line given by Eq. (5) fits the data of [14] fairly closely. It is readily apparent from Eq. (5) that at least for general aviation aircraft propellers, the A-weighted sound level follows an extremely high power dependence on tip Mach number.

In the more recent study performed by Heller et al [16], Mach number relationships were determined for harmonic levels of two- and three-bladed propellers in the 100 to 150 kW class. Heller et al derive an empirical prediction equation for the A-weighted harmonic sound pressure levels in the form

$$L_{Amax}^{(m)} = 10 \log_{10} \left[M_h^n \, P^{1.5} \right] - 20 \log r + C_m \quad \text{dB} \qquad (6)$$

For the two-bladed propellers, the exponent n is given by [16]

$$n = 19.7 \, (\log_{10} m)^{2.2} + 4.4 \qquad (7)$$

but the corresponding equation for the three-bladed propellers is not given.

Analysis of the results in [16] shows that the exponents for both two- and three-bladed propellers can be expressed in a simple relationship if the product (mB) is used as variable instead of m. Values of the exponent are shown in Figure 12, and it is seen that the linear regression line given by the equation

$$n = 1.57 \, mB - 1.3 \qquad (8)$$

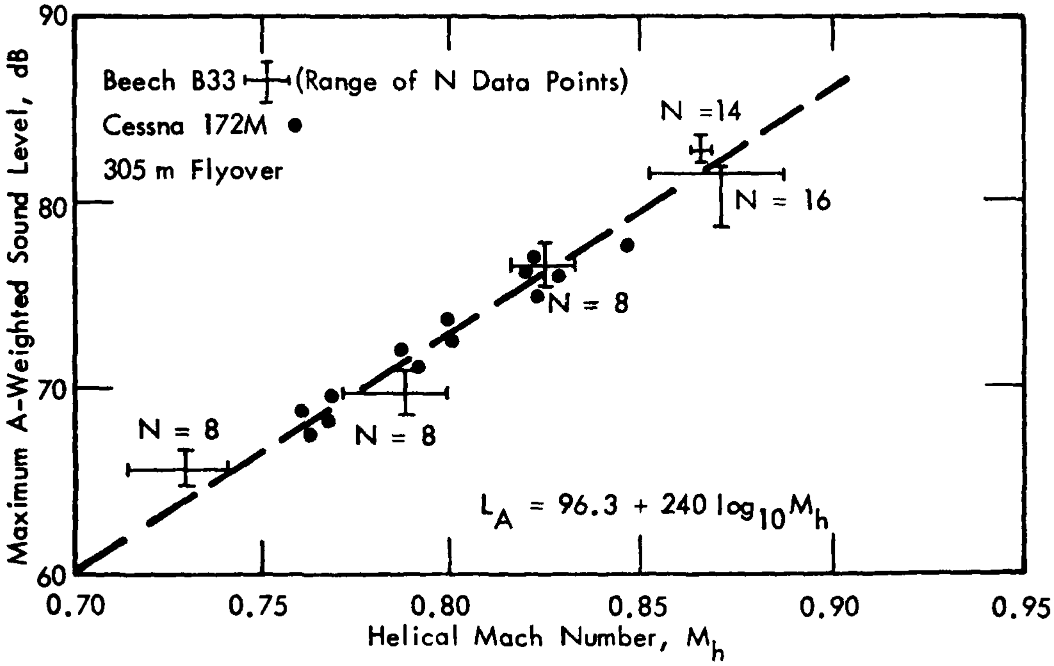


FIGURE 10. VARIATION OF MAXIMUM A-WEIGHTED SOUND LEVEL WITH PROPELLER HELICAL MACH NUMBER [13]

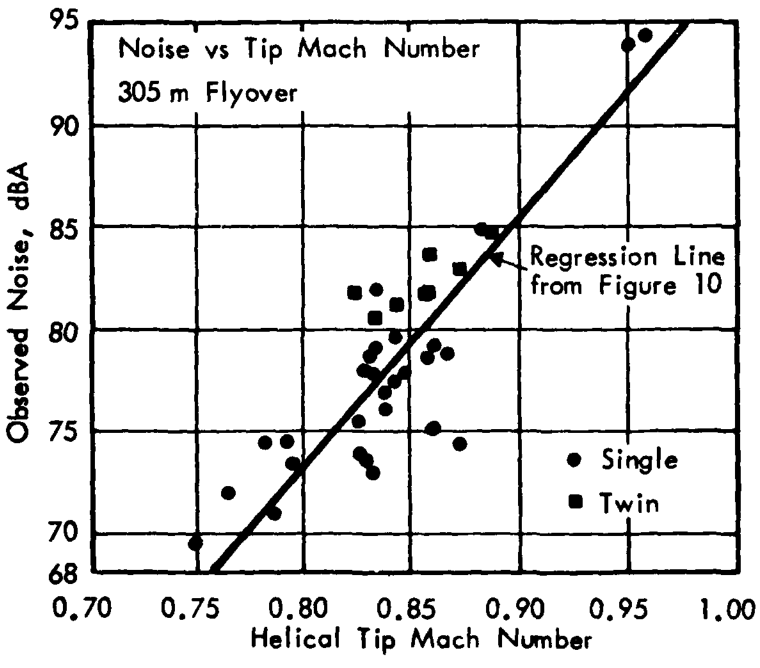


FIGURE 11. OBSERVED FLYOVER NOISE LEVELS AS A FUNCTION OF HELICAL TIP MACH NUMBER [14]

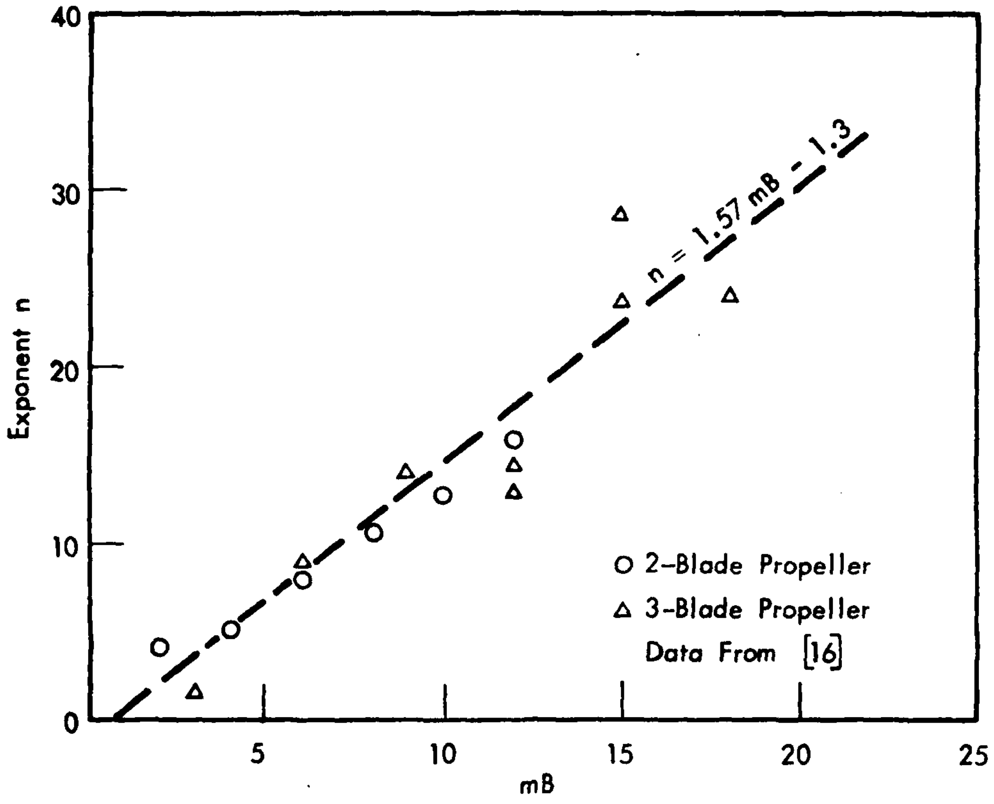


FIGURE 12. EXPONENT OF MACH NUMBER IN RELATIONSHIP WITH A-WEIGHTED SOUND LEVEL (EQUATION (5))

provides a good fit to the data points. It is interesting to note that if a linear relationship were assumed between P and M_h, then the exponent of tip Mach number would be given approximately by

$$n' = 1.57 \text{ mB} \tag{9}$$

with $$L_A(m) = 10\, n' \log_{10} M_h - 20 \log r + C_m \quad \text{dB} \tag{10}$$

The results of Heller et al and Galloway are consistent if it is assumed that the overall A-weighted sound levels are dominated by harmonic orders for which n' has a value of 24. Using Eq. (9), this condition implies that m = 7 or 8 for a two bladed propeller and m = 5 for a three-bladed propeller. Since the test conditions used by Galloway [15] involved fairly high propeller helical Mach numbers (0.75 - 0.9), it is to be expected that high order harmonics would make a significant contribution to the A-weighted levels.

The value of n' given by Eq. (9) is less than the exponent 2mB which would result from the first term in the Bessel function in Eqs. (2) and (3). However, it has been shown in the discussion of Eq. (4) that, because of negative terms in the expansion for the Bessel function, the effective exponent would be less than 2mB. Thus the test data seem to be in reasonably good agreement with the analysis.

The observation that the Mach number exponent in Eq. (5) results from the dominance of higher order harmonics in determining A-weighted sound levels means that the equation is valid for only a certain range of tip Mach numbers. Figures 10 and 11 suggest that, below a tip Mach number of about 0.75

the measured A-weighted sound levels vary with Mach number at a rate slower than the 24th power. This is to be expected because as tip Mach number decreases the contributions from the higher order harmonics become less, and lower order harmonics, which vary more slowly with Mach number, become dominant.

This result is confirmed by measurements at lower tip Mach numbers. For example, measurements have been made on aircraft such as the Lockheed L-382, British Aerospace 748, de Havilland Canada DHC-7 and Shorts SD-330 for a range of operating conditions which include propeller tip helical Mach numbers of 0.66 to 0.81, and engine power of 170-3200 kW (230-4300 hp). Regression lines fitted to the data show that the peak overall A-weighted sound level L_{Amax}, for an airplane with N engines, follows a relationship such as:-

$$L_{Amax} = 10 \log_{10} (N.P) + 66 \log_{10} M_h - 19.1 \log_{10} r + C \qquad (11)$$

where C = 103.2 when P is expressed in kilowatts and r in meters, or C = 111.8 when P is expressed in horsepower and r in feet. (This equation corresponds to Eq. (1) for EPNL.)

Unlike the data for light aircraft used to develop Eq. (5), the sound levels associated with Eq. (11) include a significant contribution from engine sources as well as the propeller. This can be seen in narrowband spectra such as those shown in Figures 4 and 5. Consequently Eq. (11) represents the sum of propeller and engine noise rather than propeller noise alone. In order to isolate the discrete frequency contributions from the propeller, components at the propeller blade passage harmonic frequencies were identified in narrowband spectra. The harmonic levels were corrected

for ground reflection effects and normalized to conditions for a single propeller at 305m (1000 ft), 1490 kW power (2000 hp) and tip helical Mach number of 0.8. The resulting normalized sound pressure level, SPL', given by Eq. (12)

$$SPL'(mB) = SPL(mB) + 20\log\frac{r}{305} - 10\log N - 10\log\frac{P}{1490} - 70\log\frac{M_h}{0.8} \quad (12)$$

is shown in Figure 13 in terms of the product, mB, of harmonic order and number of blades. The data show a good collapse, especially when one considers the difficulties in accurately estimating ground reflection effects for harmonic components whose levels are comparable to broadband levels. In Eq. (12) distance r is in meters and engine power P in kW. SPL (mB) is the harmonic sound pressure level for an airplane with N propellers.

In general the data in Figure 13 represent the four harmonics of order m = 1 to 4, these being the only harmonics which could be positively identified in the measured narrowband spectra. The exceptions are the two cases where M_h is 0.8 or greater, and in those cases harmonic components were identified up to m = 5 and m = 8, respectively. As identified in the figure, the data are associated with propellers having 4 or 5 blades.

Other factors which have been found empirically to have significant effects on A-weighted sound levels are tip thickness-to-chord ratio, and propeller installation. Data on tip thickness effects are given in [14] and reproduced in Figure 14. Although there are no specific details for the propellers associated with the measurements in Figure 14, the data can be used to construct an empirical curve relating tip thickness

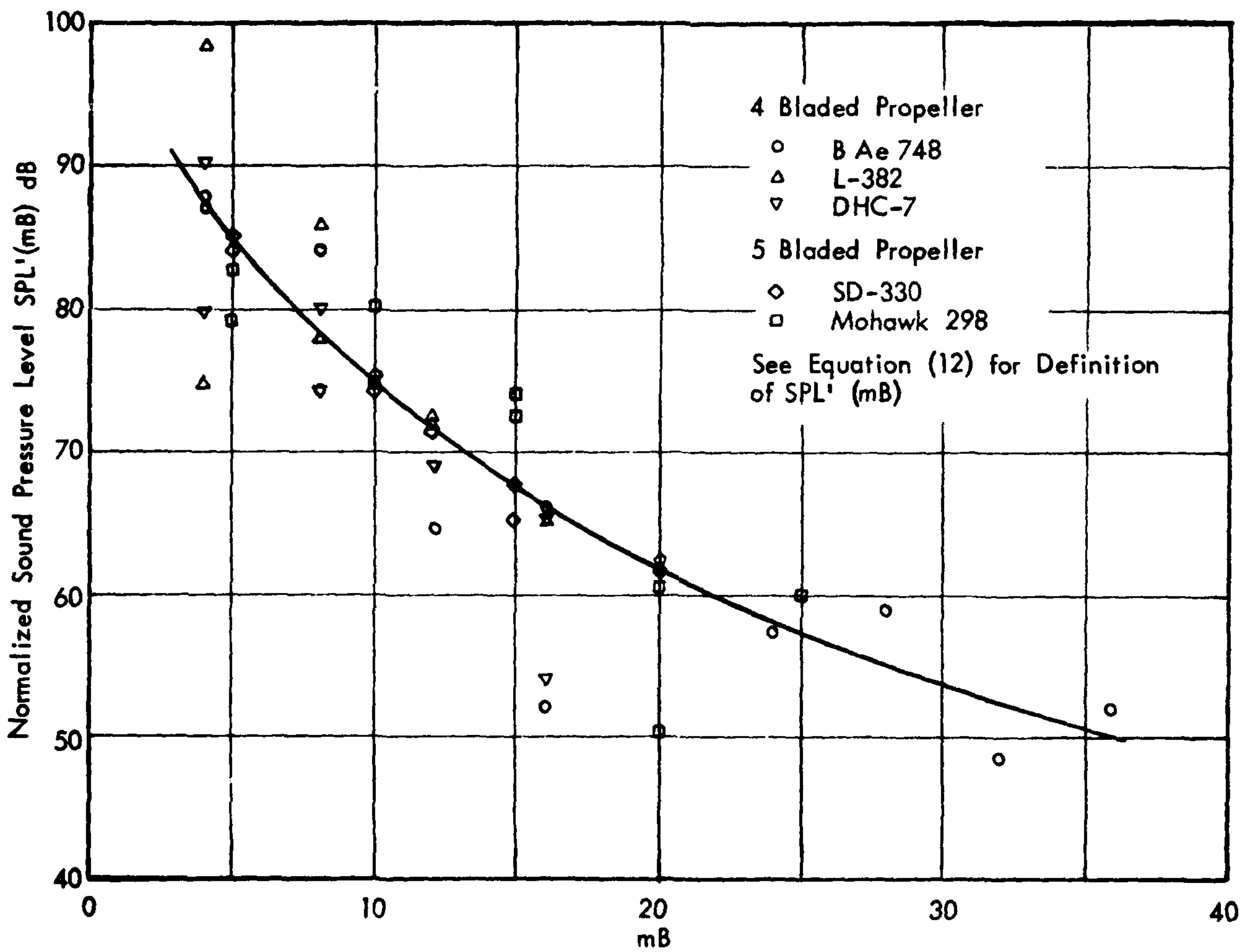


FIGURE 13. NORMALIZED SOUND LEVEL FOR PROPELLER HARMONICS MEASURED FOR PROPELLERS WITH MACH NUMBERS LESS THAN 0.81

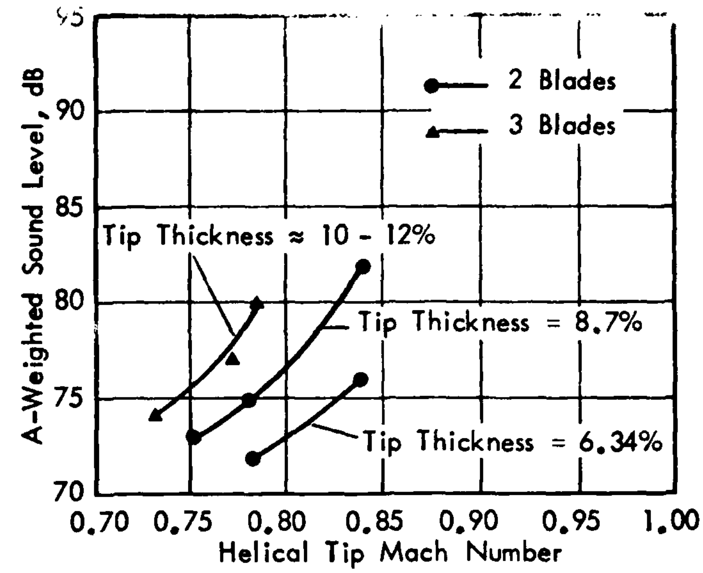


FIGURE 14. VARIATION OF A-WEIGHTED SOUND LEVEL WITH BLADE TIP THICKNESS [14]

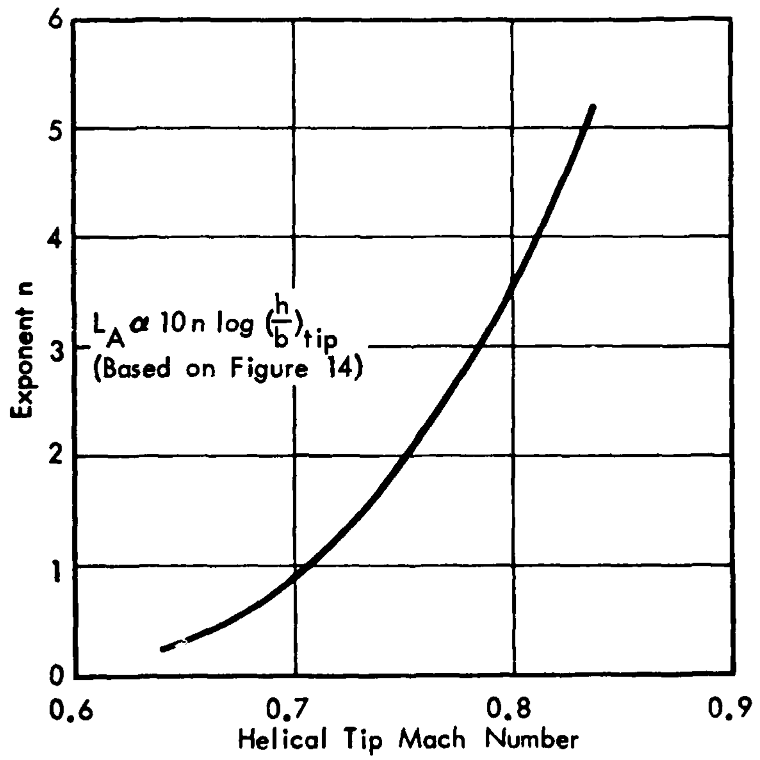


FIGURE 15. EXPONENT OF THICKNESS: CHORD RATIO FOR A-WEIGHTED SOUND LEVEL

and A-weighted sound level for a range of Mach numbers. Assuming that

$$L_A \propto 10n \log (t_B)_{tip} , \tag{13}$$

then Figure 14 gives values of n which are shown in Figure 15. It is seen that n increases markedly with tip Mach number from a value of about 0.9 at M_h = 0.7 to 3.5 at M_h = 0.8. This relationship between t_B and M_h suggests that the exponent may be dependent on harmonic order. As is indicated in [15], the effect of tip thickness is important because it is common practice to cut down the diameter of an existing blade without changing the blade sectional characteristics. While the reduced diameter lowers the tip Mach number, the benefit in noise reduction is substantially offset by the increase in noise level due to increased blade thickness.

Installation effects are usually considered to have a negligible influence on far field noise levels except where the effects are associated with the use of pusher propellers. Static test results, such as those presented in [17], show a pusher propeller generates much higher noise levels at higher harmonic order than does a tractor propeller. Similar results are claimed for flight tests, indicating that the effects of inflow disturbances are still present for the pusher propeller even when there is forward motion.

4.3 Propeller Noise Prediction Methods

Prediction methods for propeller noise are important in the present context since they can be used to estimate the effects of different noise control approaches. The methods

can be divided into two groups--those which are based on empirical data and those which are solely analytical. In recent years the general trend has been away from empirical methods to analytical approaches. The reasons for this trend are apparent from the discussion in the preceding sections of this report.

Early empirical prediction methods were based mainly on propeller static tests and, as a consequence, were susceptible to the inflow turbulence problems discussed earlier. Recent flight data of Galloway [13] and Heller et al [16] discussed in Section 4.2.2 do not have inflow turbulence problems but the resulting prediction methods are limited, implicitly, to general aviation operations. A more general prediction method, which is based to some extent on empirical data, is that of the SAE Aerospace Information Report AIR 1407 [18]. The procedure is in the form of a series of charts which predicted perceived noise level and A-weighted level from the overall sound pressure level. The charts show that the overall acoustic power π has the following approximate relationship

$$\pi \propto P^{1.6} M_T^{5.4} B^{-1.9} D^{-2.0}. \qquad (1$$

When the conversion is made to A-weighted sound level, it is dependent on propeller diameter and tip helical Mach number, M_h, with the exponent of M_h varying with diameter and Mach number. For example, when $M_h = 0.85$, the exponent of M_h varies from about 3 for small diameters to about 6 for large diameters. The corresponding values of the exponent when $M_h = 0.6$ are approximately 1 and 2, respectively. The values of the exponents are significantly lower than that of 24 determined by Galloway [13] even when the exponents for M_h, M_r and P are all combined

The analytical models [1,8,10,11] developed for propeller noise can be used as prediction methods, and several comparisons have been made between measured and predicted sound levels [8,10,11,12,19]. All the comparisons utilize data from the same flight test series using a DHC-6 Twin Otter airplane [12,19]. The test propellers have three blades, a diameter of 2.60 m (8.53 ft), a tip rotational Mach number of 0.85, and an airplane Mach number of 0.12. The comparisons show varying degrees of agreement between measured and predicted results. For an observer in the plane of rotation of the propeller, Farassat and Brown underpredict the levels for harmonics of order 1 and 2 and overpredict for m = 4 through 7, although the maximum difference between measured and predicted levels is less than 4 dB. In general Woan and Gregorek show predicted results which are higher than the corresponding measured values, but again the differences are less than 4 dB. Somewhat larger differences (up to 10 dB) are found between experimental and predicted results in the comparison by Magliozzi [19] but in this case the tip rotational Mach number is lower, at 0.78.

Perhaps the best agreement between predicted harmonic levels and measured data is that achieved by Succi [11] for a range of propeller speeds. In general the discrepancy between measured and predicted levels is less than 2 dB.

These comparisons provide an indication of the accuracy likely to be achieved by analytical prediction procedures. However, in order to make use of the procedures, it is necessary to have a fairly detailed description of the characteristics of the propeller-blades. The necessary details may not always be available, particularly in a general study such as the one

discussed in this report. In such circumstances a combination of analytical and empirical prediction procedures has to be utilized in order to obtain general trends.

4.4 Noise Control

The preceding discussion has identified several possible approaches to reduce propeller noise. This section will describe the potential of several of these methods on the basis of either analytical or experimental studies. It has to be borne in mind throughout the discussion that changes to a propeller for acoustic reasons will have associated aerodynamic implications. These aerodynamic side effects have not always been considered in acoustic studies in the past.

A recent analytical study has been performed by Klatte and Metzger [20] for three general aviation aircraft in the weight range 1,360 kg (3000 lbs) to 5,670 kg (12,500 lbs) and propeller tip helical Mach numbers of 0.80 to 0.90. The basic assumption of the study was that the performance of the aircraft would not be affected by the noise control approaches. Also, a constraint was imposed in that the propeller rpm could not be reduced as such a change would involve modifications to the engine or gear box. Propeller parameters selected for study include airfoil section, tip thickness and planform, propeller diameter and number of blades. The maximum reductions achieved in the A-weighted sound level for the propeller alone ranged from 5.5 dB to 13.7 dB, although when engine noise is taken into account the maximum achievable noise reductions are somewhat lower. Discussion of the above propeller parameters, and other noise control approaches, follows in this section, before the applicability of the

approaches to the study aircraft is considered in Section 5.0.

4.4.1 Tip Mach Number

It is readily apparent from the empirical relationships between A-weighted sound level and tip Mach number presented in Eqs. (5) - (10) that tip Mach number has a very strong influence on the far field noise levels. For example, measurements on a given airplane at various engine speeds show a reduction in A-weighted sound level of 15 dB for a reduction in tip Mach number of only 16% [13]. This reduction in noise level would probably be associated with a reduction in propeller efficiency and the power absorbed by the propeller, unless some other modifications, such as increased propeller diameter, increased number of blades, changes in propeller planform or changes in airfoil shape were adopted to maintain aerodynamic performance. These changes may affect the noise reductions achieved in practice.

The extreme case in low speed has been taken in the military field where audible detectability is an important problems [21-23]. Propellers used had three to six blades and operated at helical Mach numbers of 0.2 to 0.4. These propellers, however, were designed such that the maximum noise reductions were achieved under cruise conditions where minimum power was required and minimum noise produced. The aircraft had relatively low forward speeds, even in cruise, and are designed to have low cruise thrust requirements. Thus the operating conditions were significantly different from those of general aviation or large conventional propeller-driven aircraft at

takeoff conditions, and it is unlikely that the large noise reductions achieved can be reproduced for commercial aircraft. Acoustical problems encountered with these low speed propellers included interference effects from the airframe aft of the propeller but these problems arose only at the very low Mach numbers. They should not cause significant effects for general aviation and commercial operations.

The influence of tip Mach number on far field noise level, and the associated dependence of propeller diameter and efficiency has been predicted by Harlamert and Edinger [24]. Figure 16, reproduced from [24], shows the reduction in noise level and efficiency of a propeller as the tip Mach number is reduced by reducing either propeller rpm or diameter. Efficiency decreases more rapidly when diameter rather than rpm is reduced, but the converse is true for noise level. Similar results are presented by Davis [25].

Practical examples of a move to lower propeller rpm, and hence lower tip Mach number, as a means of reducing propeller noise can be found in several production aircraft powered by PT6A or TPE 331 engines. In the case of the PT6A engine, early versions had a rated rpm of 2200. This was reduced to 2000 for the PT6A-41, 1700 for the PT6A-45 which powers the Short SD330 and Mohawk 298, and 1210 for the PT6A-50 of the de Havilland Canada DHC-7. The reduced rpm were achieved even though the engine power increased from about 560 kW (750 HP) to 875 kW (1173 HP). The increase in power was absorbed by an increase in the number of blades from 3 to 4 for the DCH-7 and 5 for the SD 330 and Mohawk 298, and an increase in propeller diameter from about 2.44 m (96 inches) to 2.82 m (111 inches) for the SD 330 and Mohawk 98 and 3.43 m (135 inches) for the DHC-7.

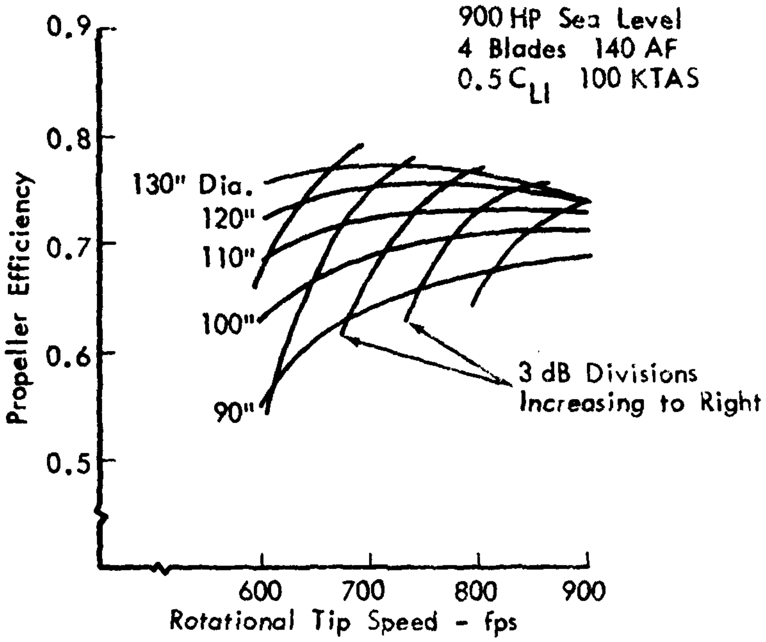


FIGURE 16. PROPELLER EFFICIENCY AND FAR FIELD NOISE LEVELS AS AFFECTED BY ROTATIONAL TIP SPEED AND DIAMETER [24]

Similarly the rpm of the TPE 331 engine has been reduced from 2000 to 1591 by the introduction of a higher gear ratio (and a change in the direction of rotation of the propeller). Early versions of the Swearingen Merlin III and Mitsubishi MU-2 operated at the higher rpm whereas, for noise reasons, the rpm was reduced on later verions of the aircraft. In the case of the MU-2, the number of blades was increased from 3 to 4 when changing to the lower rpm, and the propeller diameter increases from 2.29 m (90 inches) to 2.49 m (98 inches).

Even with the increases in propeller diameter, the tip rotational Mach number decreased with rpm in all cases, from about 0.75 to 0.64 for the PT6A and 0.70 to 0.60 for the TPE 331.

4.4.2 Airfoil Section

The blade cross-section at any radius can be changed in several ways. Firstly the maximum thickness-to-chord ratio can be altered while the basic airfoil shape is retained. Secondly, the airfoil shape can be changed, for example by going from a NACA 16 Series airfoil to a NACA 65 Series, with the thickness-to-chord ratio maintained constant. Thirdly, both properties can be changed.

Referring to Eqs. (2) and (3), it is seen that a change in thickness-to-chord ratio t_B will influence predicted thickness noise but will not change the predicted lift or drag noise components. On the basis of Eq. (2), a doubling of t_B will result in a predicted 6 dB increase in the thickness noise level generated by the associated element of the blade.

Calculations by Woan and Gregorek [10] for typical propellers with Clark Y airfoil sections show a similar relationship between thickness-to-chord ratio and sound level.

Changes in basic airfoil shape can change several factors such as the chordwise location of maximum thickness or minimum pressure, the radius of the leading edge, and the airfoil camber. Referring again to Eqs. (2) and (3), airfoil shape influences harmonic noise levels through the non-compactness factors ψ_V and ψ_L. Also, in Eq. (3), the airfoil shape may influence the lift coefficient C_L. Calculations by Hanson [1] for NACA 16 Series, NACA 4-digit Series and biconvex parabolic airfoil sections indicate that the shape has only a small effect (less than 1 dB) on thickness noise for flight conditions and harmonic orders of interest.

Corresponding calculations for lift noise were performed in terms of chordwise loading rather than airfoil shape directly. The chordwise loadings varied from "nearly uniform" to strongly peaked, with the lowest noise levels being associated with uniform loading. The calculations performed by Hanson [1] shows that for general aviation and large conventional propellers, the noise levels vary by up to 5 dB with blade loading, for harmonics such that mB is less than about 20.

Metzger et al [26] have performed static tests to compare noise levels generated by NACA 16 Series and 65 Series airfoils. Measurements in the far field show that the 65 Series airfoil is quieter by about 2 dB for the first harmonic, 10 dB for the third, and 15 dB for the ninth. In this particular case the airfoil with the lower noise levels has maximum thickness and minimum pressure locations closer to

the blade leading edge (maximum thickness occurs at about 0.42b for the 65 Series airfoil and 0.5b for the 16 Series). It has to be remembered, of course, that these are static test results, and that under flight conditions the noise levels at the higher harmonic orders may not be significant for either airfoil.

Airfoil section design, as a means of decreasing propeller noise and increasing efficiency, has been discussed recently by Davis [25]. In this case a completely new airfoil series identified as ARA-D sections, was developed. The sections are characterized by a finite trailing edge thickness, a bluff leading edge, no concavity on the upper surface and limited concavity on the lower surface. A comparison of an ARA-D section and an NACA 16 Series section, both with $t_B = 0.06$, is shown in Figure 17. It is seen that the location of maximum thickness on the ARA-D section is closer to the airfoil loading edge than it is for the 16 Series. Although the ARA-D series airfoils have not yet undergone extensive flight test measurements, it is predicted by Davis that they will result in lower noise levels without attendant weight or performance penalties. The relationship between noise reduction and propeller weight predicted by Davis for the ARA-D sections is shown in Figure 18. The claimed advantage for the ARA-D section is that propeller efficiency is maintained at the lower Mach numbers associated with takeoff. Thus takeoff performance can be achieved at reduced rpm and/or reduced diameter.

In constructing Figure 18, Davis [25] has postulated three methods of reducing noise--blade design, increase in diameter with no performance loss (probably a small gain), and change

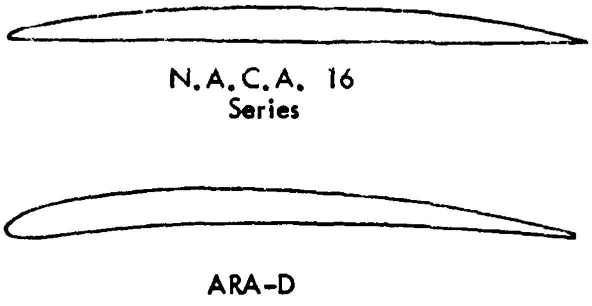


FIGURE 17. COMPARISON OF NACA 16 SERIES AND ARA-D SERIES AIRFOIL SECTIONS [25]

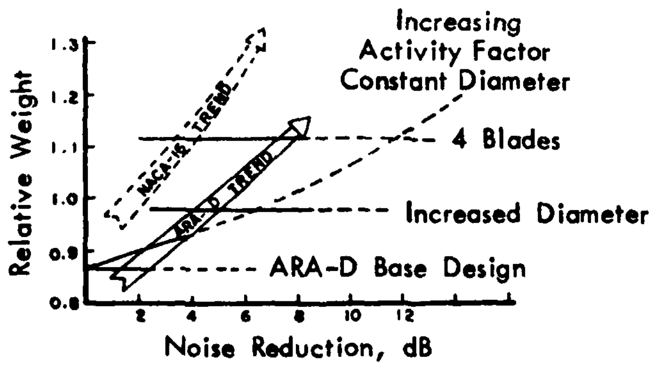


FIGURE 18. ESTIMATED WEIGHT AND NOISE REDUCTION TRENDS FOR ARA-D SECTION AIRFOILS [25]

of blade number. Figure 18 presents propeller weight using the baseline NACA 16 Series airfoil as a reference. Thus, for example, it is predicted that the weight of the ARA-D base design will be about 14% lower than that of the equivalent NACA 16 Series propeller, and the A-weighted noise level about 3 dB lower. Increasing propeller diameter or number of blades will increase both noise reduction and propeller weight. Typically, it is predicted by Davis [25] that the ARA-D sections will achieve noise reductions of about 4 dB without loss of performance or change of diameter, and, possibly, with a saving of weight.

4.4.3 Propeller Diameter

The influence of propeller diameter on far field noise levels is closely involved with tip Mach number and propeller efficiency, as has been shown by Harlamet and Edinger [24] and Davis [25]. Data from these two references are reproduced in Figures 16 and 18, and the results have been discussed in Sections 4.4.1 and 4.4.2. Succi [11] has predicted the change in noise level for a typical general aviation propeller such as that installed on a Cessna 172 airplane. The propeller has an NACA 16-506 airfoil section and has the planform of a McCauley 1C160 propeller. The diameter is 1.93 m (76 inches) and the tip rotational Mach number 0.81. The predicted change in A-weighted sound level associated with a 20% reduction in propeller diameter is 8 dB, with a 4 dB change in unweighted sound pressure level. This difference between weighted and unweighted noise reductions is attributed to a shift of acoustical energy to the lower order harmonics as diameter decreases.

It is assumed by Succi [11] that the planform remains the same as diameter changes and that the propeller absorbs the engine power at maximum rpm. However, the efficiency of the propeller decreases with diameter (a decrease of about 4.5% as diameter decreases 20%), so that less power is converted into thrust. Some of the efficiency loss may be regained by changes to planform, but there may be associated effects on noise level.

4.4.4 Number of Blades

It has been recognized for some time that increasing the number of blades of a propeller, while at the same time reducing propeller diameter, will reduce the overall noise level, and early work by Hubbard [27,28] produced noise charts for light aircraft and transport airplanes which demonstrated the effect of blade number. A recent example of an increase in number of blades from 4 to 8 is given by the Antonov AN-24 [29].

Succi [11] has predicted the variation of overall sound level and A-weighted sound level with number of blades for a typical general aviation airplane at full power in level flyover. The blade has an NACA 16-506 airfoil section, a 1.93 m (76 inch) diameter, and a tip rotational Mach number of 0.81. The assumptions are made that the lift coefficient and thrust are the same for all propellers. Then the solidity at each radius is approximately constant and the blade chord is inversely proportional to the number of blades. The results show that the unweighted overall sound level varies, approximately, as $-20 \log B$, whereas the A-weighted sound level varies as $-8 \log B$, approximately. The difference in dependency on

blade number B arises because an increase in the number of blades shifts the acoustical energy to higher frequencies which make relatively greater contributions to the A-weighted sound level.

Calculations by Woan and Gregorek [10] show a much smaller reduction in sound level when the number of blades is increased. However, in that case the blade chord is constant, so that the solidity increases. This difference between the two studies emphasizes the difficulties which can arise when not all of the relevant parameters are considered.

4.4.5 Blade Loading

Aerodynamic load distributions on a propeller blade can be changed in either the chordwise or radial directions by changes to airfoil section, planform and twist. The influence of chordwise loading has been included in the discussion of the airfoil section. Thus the present comments refer only to the radial load distribution.

It has been seen earlier in Section 4.4.4, that a reduction in propeller diameter (for a constant rpm) produces a reduction in noise level. This change can be explained crudely in terms of moving the blade load further inboard. A similar shifting of the blade load can be achieved by changing either the spanwise distribution of blade twist or the planform of the blade. Examples of these changes have been described by Succi [11] for a typical general aviation propeller with a blade diameter of 1.93 m (76 inches), an NACA 16-506 airfoil section and a tip rotational Mach number of 0.81. It was assumed in the analysis that lifting line theory was valid; that is the chord must be small relative to the radius.

The conclusions reached by Succi for the specific conditions considered are that significant noise reductions can be achieved when the peak load is moved inboard from 80% of the radius to 60% but that the deterioration in efficiency is much less if the radial load is shifted as a result of planform changes than as a result of twist distribution changes. The results of the calculations show that the change in A-weighted sound level is about 4.5 dB when the peak load is moved from $0.8r_T$ to $0.6r_T$. The corresponding losses in efficiency are about 3.9% due to retwisting of the blade and 1.0% due to a change in planform.

4.4.6 Blade Sweep

The noise reduction potential of blade sweep has been investigated analytically by several authors without achieving significant changes in noise level. Succi [11] considered a basic two-bladed propeller with an NACA 16-506 airfoil section and a tip rotational Mach number of 0.8. The sweep was assumed to be in the form of a curved centerline for the blade, with a range of total sweep angles from hub to tip being studied. The predicted changes in A-weighted sound level were small for practical sweep angles, with the noise reduction being 2.5 dB for a tip sweep angle of 60°.

Woan and Gregorek [10] consider tip sweep on a two-bladed propeller with a Clark Y airfoil section. The tip rotational Mach number was 0.9, the maximum thickness-to-chord ratio either 6% or 10%, and the sweep occurred in the outer 15% of the tip radius. The maximum predicted reduction in harmonic level was 3 dB, occurring at harmonic orders between 15 and 35. There were negligible changes in noise level for the five lowest order harmonics.

A third investigation by Farassat and Brown [8] considered a helicopter rotor. In this case noise reductions of about 3 dB were achieved for the low order harmonics and reductions of up to 6 dB were obtained for higher order harmonics. However, although the tip rotational Mach number of 0.8 was similar to that of the above two general aviation cases, it should be noted that the rotor tip was transonic during part of the rotation cycle because of the forward motion of the helicopter. Tip sweep could be expected to provide greater benefits in such a condition, as it does on a propeller with a supersonic tip helical Mach number.

One situation where blade sweep may give a significant benefit in far field noise of general aviation aircraft is the case of a pusher propeller. A swept blade leading edge would cancel the fluctuating forces caused by a given inflow distortion pattern, thereby reducing the dominant noise source for the pusher design [30]. A second situation is that of transonic or supersonic tip speeds, such as in the Prop Fan propulsion concept [1]. However, these high tip speeds will not be encountered with conventional propeller designs.

4.4.7 Tip Shape

The term "tip shape" can include factors such as thickness-to-chord ratio, planform and out-of-plane modifications. The influence of thickness-to-chord ratio t_B has been discussed earlier, and the effect on far field noise level was shown in Figure 14. Increasing the value of t_B causes large increases in A-weighted noise level, the increase being about 6 dB for a doubling of t_B.

Changes in tip planform were studied, for example by Brown and Ollerhead [23] who compared swept and trapezoidal shapes with a conventional planform. No significant changes in noise level were observed. However, a more recent analysis by Klatte and Metzger [20] for three general aviation aircraft indicates that modification of tip planform can produce reductions of 0.5 to 2 dB in the A-weighted sound level. In all cases the lower noise levels are associated with an elliptical planform.

Finally, Hartzell Propeller Inc. introduced a novel modification to tip shape in the form of what is essentially a tip end plate on each blade, the blade being bent through an angle of 90° [31]. The presence of the end plate influences the formation of the tip vortex and blade loading. It has been claimed that a reduction in diameter of 51 mm (2 inches) can be achieved by use of these so-called "Q" tips without loss of takeoff or climb performance. No test data have been published, but it has been stated that the modified tip results in lower cabin noise levels, presumably because of the increased clearance between propeller tip and fuselage sidewall. However, no definite claims have been made for reducing far-field or near-field noise levels.

4.4.8 Unequal Blade Spacing

Studies have been performed by Shahady et al [32] on propellers with "modulated" or unequal blade spacing. The objective of the studies was to redistribute the harmonic sound energy into a series of multiple tones of lower sound power level. The studies included analytical work, and tests in a static propeller whirl rig facility using a 6-bladed propeller with

a diameter of 2.8 m (9.33 ft) and an NACA-0015 airfoil section. Tip rotational Mach numbers ranged from 0.26 to 0.52. The results of the studies have been interpreted by Shahady et al as showing that the unequal blade spacing has some advantage in reducing audible detectability. However, the data show that the baseline propeller with equal blade spacing generated the lowest A-weighted sound levels.

4.4.9 Ducted Propellers

Ducted propellers have been studied experimentally for both tractor [33] and pusher [14,17] designs, but only in the case of the tractor configurations were any noise reductions achieved. Pusher propellers operate in a region of high inflow turbulence, which is the main cause of the rotational noise. The installation of a duct or shroud will have little or no influence on this turbulence and the radiated noise levels. Some test data [14,17] even show that the noise levels <u>increased</u> when a free pusher propeller was replaced by a shrouded propeller with the same tip rotational Mach number (but with 3 blades instead of 2).

Trillo [34] has reviewed the use of ducted propellers on surface effects vehicles and has found that significant reduction in far field noise levels can be achieved for a given static thrust. The first generation (1973-1974 time period) of ducted propellers achieved reductions in A-weighted noise levels of about 10 dB. More recent designs (1977 time period) show further noise reductions of 5 to 10 dB.

A recent study of ducted tractor propellers on a general aviation airplane was conducted by Dowty Rotol and reported by

Davis and Kemp [33]. The design consisted of a seven-bladed fan with six flow-straightening vanes which supported the surrounding duct (Figure 19). Prototype units powered by Avco Lycoming IO-540 (300 hp) engines have been demonstrated on a twin-engined, high-winged general aviation airplane with a takeoff weight of about 6000 lbs. The two free propellers of the standard airplane had a diameter of 80 inches. These were replaced with 34-inch diameter fans. The tip Mach number was reduced from 0.84 to 0.50, and, it is claimed, the A-weighted noise level was reduced 20 dB, from 85 dBA to 65 dBA. It is further claimed by the manufacturers that the sound level would have been reduced only 10 dB by increasing the number of blades on the free propellers to 5 and decreasing the diameter to 64 inches. This is a 20% decrease in diameter with respect to the 3-bladed design. (This noise reduction statement is inconsistent with the data from [14,17]).

Performance advantages claimed for the Dowty Rotol system included improved propeller tip efficiency, and a 20% increase in take-off thrust due to the supercharging effect of induction air entering the engine from within the duct area and thrust augumentation associated with expulsion of compressed, high-velocity air from duct exhaust. Cruise thrust is equal to that produced by standard propellers but, as the test airplane has a low cruising speed of about 165 mph, the performance capabilities have still to be proven for faster airplanes, such as the Aerostar 600/601 series, with cruise speeds of 250-290 mph. There is also a severe problem of impaired visibility for twin-engined aircraft because of blockage by the propulsor ducts. These problems are not relevant to a surface effects vehicle, which probably explains why the ducted propeller has received fairly wide application in that field.

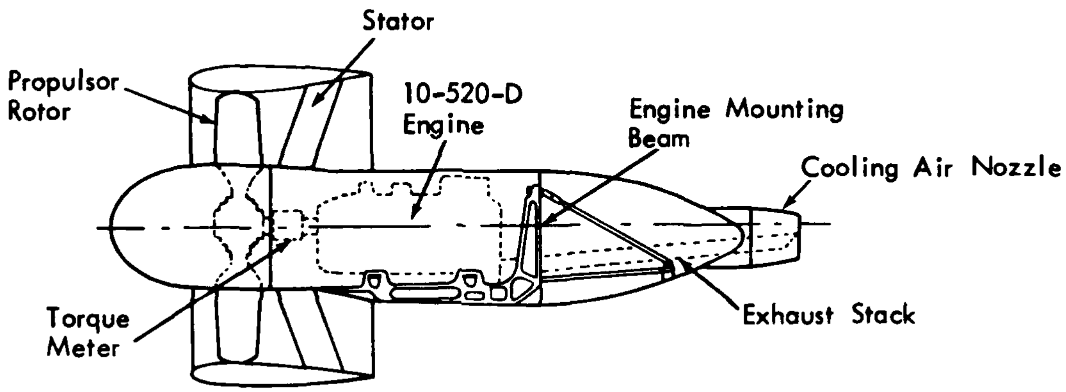


FIGURE 19. TEST SET-UP FOR DOWTY ROTOL DUCTED PROPULSOR [33]

4.5 Propeller Design

Several of the noise control methods described in Section 4.4 involve increases in propeller weight or changes in blade shape. The increases in weight are associated with increases in the number of blades or the propeller diameter as the propeller rpm is reduced. Changes in blade shape may involve variations in tip planform, blade airfoil section, or blade twist. However, recent advances in blade design [35], whereby composite materials are used instead of aluminum, will minimize the weight penalty and will provide freedom to model any desired shape. These composite blades include developments of the Hamilton Standard design with molded fiberglass on aluminum or steel spars, and a Hartzell design which uses Kevlar material [24]. The Kevlar blade has been undergoing tests on a CASA C-211 airplane powered by Garrett TPE-331 engines.

An indication of the weight saving provided by the use of composite materials can be obtained from a comparison of weights for aluminum and Kevlar blades [31]. The data refer to 4- and 5-bladed propellers and show that the weight of aluminum propeller is, on the average, 28% greater than that of a comparable Kevlar composite blade.

5.0 APPLICATION OF NOISE CONTROL TECHNOLOGY TO REPRESENTATIVE AIRCRAFT

Propeller noise control technologies for airplanes that can be expected to be placed in service during the 1980's have been reviewed in Section 4 of this report. The degree to which current technology might be used to minimize turboprop airplane noise can best be explored by application of the technology to representative airplane designs. Four different airplanes are considered in this study, representing two new designs and two that are assumed to be derivations of hypothetical existing aircraft.

In very general terms, the four study airplanes may be described as follows:

Airplane 1

A new 6 seat, single-engined, pressurized airplane, suitable for owner-flown business uses. The engine for the baseline airplane is a de-rated version of the lowest horsepower model of the PT6A series. The baseline airplane complies with FAR Part 36, Appendix F, noise limits with a several decibel margin, and is more than 10 decibels below the Stage 3 noise limits of Appendix C.

Airplane 2

A new 28 passenger, twin-engined, pressurized, transport category airplane intended for short haul commuter airlines. The engines are new technology, low fuel consumption, in the 1120 kW (1500 hp) range. The baseline airplane noise levels

are more than 5 decibels below the Stage 3 noise limits for approach, and more than 10 decibels below the noise limits for takeoff and sideline.

Airplane 3

A derivative design, 30 passenger, twin-engined, pressurized, transport category airplane suitable for local service airlines. The airplane uses existing Rolls-Royce Dart engines rated at 1648 kW (2210 hp). The baseline airplane can barely comply with Stage 2 noise limits on approach, has a margin of about 5 decibels on sideline and takeoff if a power reduction takeoff procedure is used, or about 2 decibels on takeoff with no power reduction. The airplane could be made to comply with Stage 3 noise limits with appropriate noise control measures.

Airplane 4

A derivative design, 11,340 kg (25,000 lb) payload, twin-engined transport category airplane primarily suited to cargo service. Allison 501 series engines are used at a 3542 kW (4750 hp) rating. The baseline airplane can marginally comply with Stage 3 noise limits by using power reduction on takeoff and a tradeoff of exceedances at takeoff and sideline by a margin on approach.

5.1 Specifications for Study Airplane

Relatively few of the myriad specifications for an aircraft are pertinent in an analysis of noise produced on the ground by an aircraft in flight. The significant parameters are those that describe the basic noise properties of the engine

installation and those that determine where the aircraft is in space during takeoff and approach operations. In Section 6 of this report, where cost and performance are evaluated, the additional factors of fuel consumption and operating costs will be considered. For those analyses payload, range at maximum payload, fuel consumption at cruise, and direct operating costs per airplane mile are employed. The pertinent parameters for each of the study aircraft are listed in Table 5.3.

5.2 Baseline Acoustic Characteristics

Baseline acoustic characteristics of the four study aircraft were developed in terms of one-third octave band sound pressure level (SPL) spectra associated with the maximum tone-corrected perceived noise level (PNLTM) during a flyover at a specified engine power, reference airspeed and reference distance. These spectra, in combination with their related directivity information and airspeed, are used to derive values of effective perceived noise level (EPNL) as a function of slant distance from an observer on the ground, at the point of closest approach to the aircraft flight path.

The engine power settings selected are those associated with takeoff and approach conditions, with an additional cutback power setting being chosen for Aircraft 3. Reference distances for the baseline spectra shown in Figures 20 through 23 were arbitrarily selected as 305m (1000 ft) for takeoff and cutback, and 152m (500 ft) for approach. The spectra are composed of three main components--engine broadband noise and propeller and engine discrete frequency noise. Ground reflection effects, which often distort propeller harmonic levels at low frequencies, have been omitted, but in any case their influence on perceived noise level would be small.

TABLE 3

SPECIFICATIONS FOR STUDY AIRPLANES

Parameter	Airplane 1	Airplane 2	Airplane 3	Airplane 4
Takeoff gross weight, kg (lb)	1,905 (4,200)	9,525 (21,000)	16,324 (36,000)	40,8[illegible]3 (90,000)
Payload, passengers or weight, kg (lb)	6	28	32	11,340 (25,000)
Takeoff power per engine, sea level static, kW (hp)	298 (400)	1,119 (1,500)	1,644 (2,210)	3,544 (4,750)
Propeller diameter, m (ft)	1.98 (6.5)	3.20 (10.5)	3.66 (12)	4.27 (14)
Number of blades	3	4	4	4
Propeller rpm, takeoff power	2,200	1,300	1,400	1,0[illegible]0
Range at 60 percent payload, with 45 min. reserve, km(n.m.)	1,909 (1,031)	1,698 (917)	2,574 (1,390)	4,06[illegible] (2,194)
Range at maximum payload, with 45 min. reserve, km(n.m.)	1,233 (666)	283 (153)	1,683 (909)	1,672 (903)
Cruise fuel consumption, kg/hr (lb/hr)	85 (187)	433 (953)	736 (1,620)	1,109 (2,440)
Cruise speed, km/hr (kt)	394 (213)	602 (325)	555 (300)	587 (317)
Takeoff distance, m (ft)	518 (1,700)	610 (2,000)	762 (2,500)	1,067 (3,500)
Climb airspeed, km/hr (kt)	185 (100)	241 (130)	231 (125)	231 (125)
Initial climb gradient	0.160	0.188	0.150	0.135
Approach speed, km/hr (kt)	157 (85)	204 (110)	222 (120)	[illegible] ([illegible])

The propeller noise discrete frequency components in the baseline spectra were predicted by means of Eq. (12) and Figure 13. This method was used because the ranges of propeller tip Mach number and engine power for the study aircraft were similar to those associated with the data in Figure 13. Propeller noise is responsible for the low frequency peaks in Figures 20-23, but in most cases the harmonic levels decrease rapidly with increasing harmonic order because of the relatively low tip Mach numbers associated with the baseline operating conditions. Except for Airplane 3, the propeller tip helical Mach number is always less than 0.75. In the case of Airplane 3, the tip Mach number is about 0.81 at takeoff condition and there are significant contributions from harmonics up to about $m = 5$. Even so the contribution from the higher order harmonics is much lower than for light aircraft propellers where the tip helical Mach number can be as high as 0.9.

Engine noise levels, both broadband and discrete frequency, were predicted by extrapolation of levels measured on aircraft with similar engines. This procedure was followed because the engines projected for the time frame of interest will differ little from current designs. Thus the prediction method should be reasonably accurate. Noise from engine compressors appears as discrete frequency components at harmonics of the blade passage frequency, or as peaks in the one-third octave band spectra. For the study aircraft, the compressor noise peaks occur at frequencies above 2000 Hz. Sound levels associated with compressor noise vary from engine to engine, and are especially high for Aircraft 3 at approach condition (Figure 22). Discrete frequency peaks occur also at frequencies below the compressor blade passage frequency (see, for example, Figure 4) and these are associated with other rotational noise sources

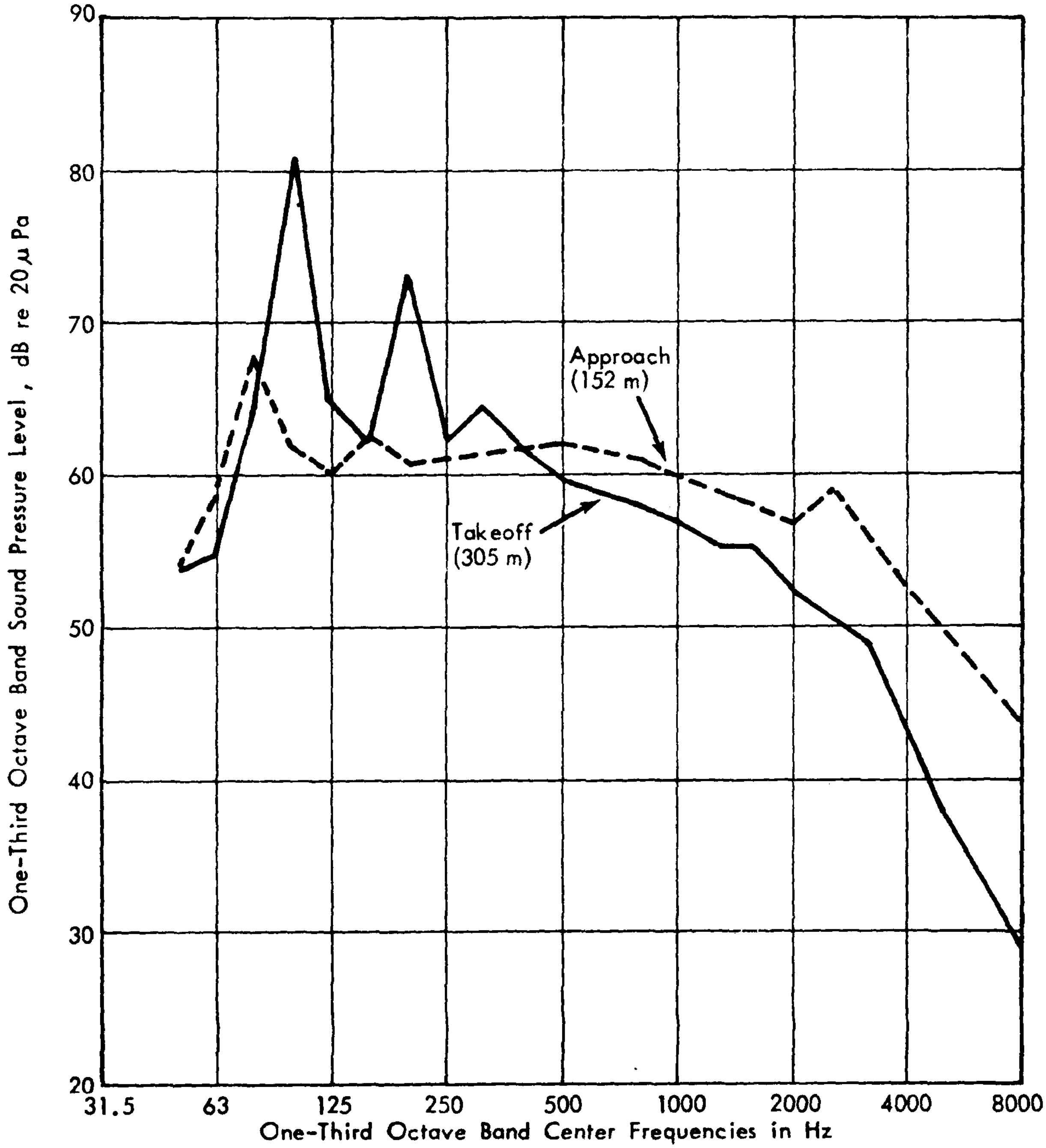


FIGURE 20. BASELINE SPECTRA: AIRPLANE 1

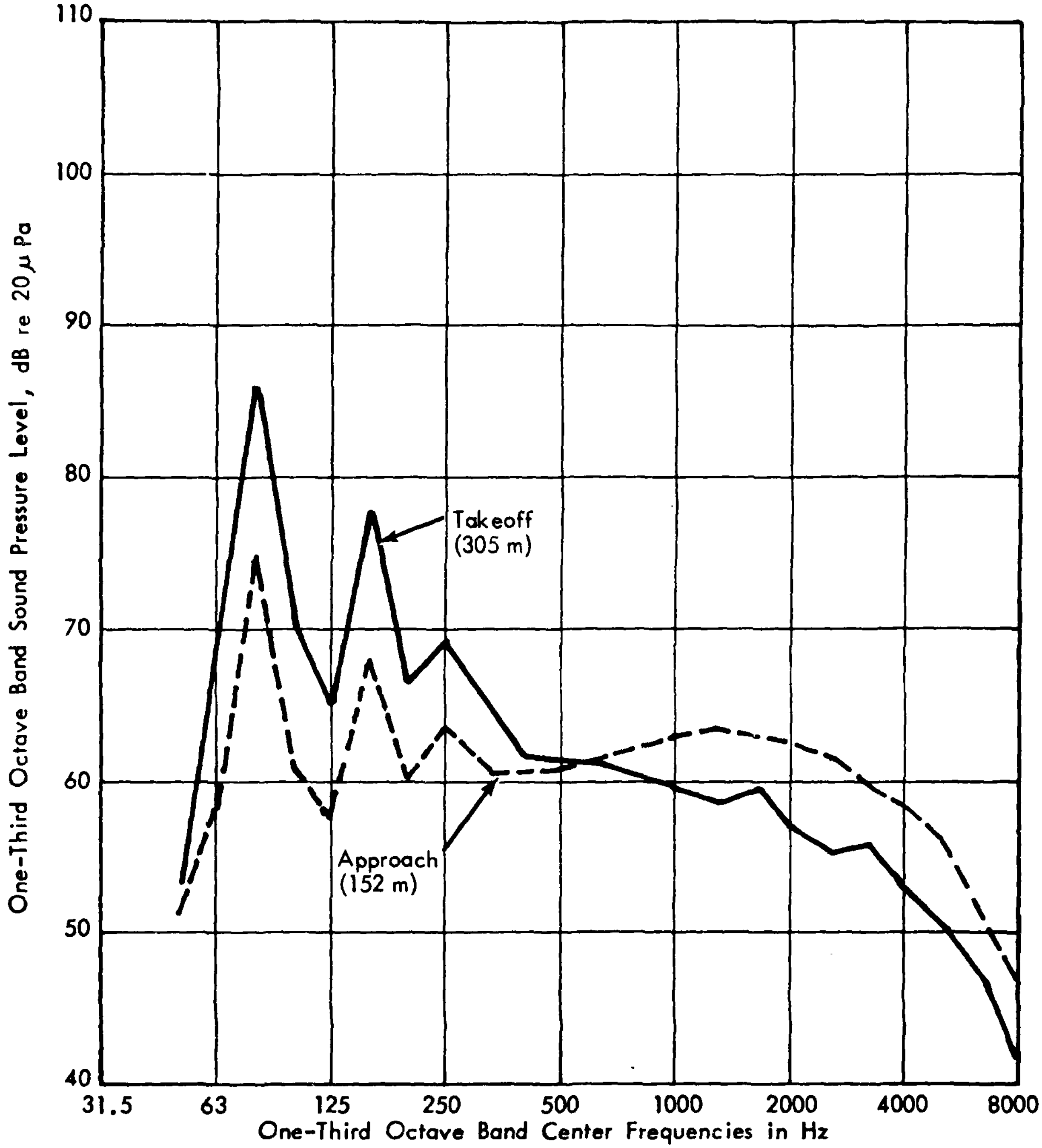


FIGURE 21. BASELINE SPECTRA: AIRPLANE 2

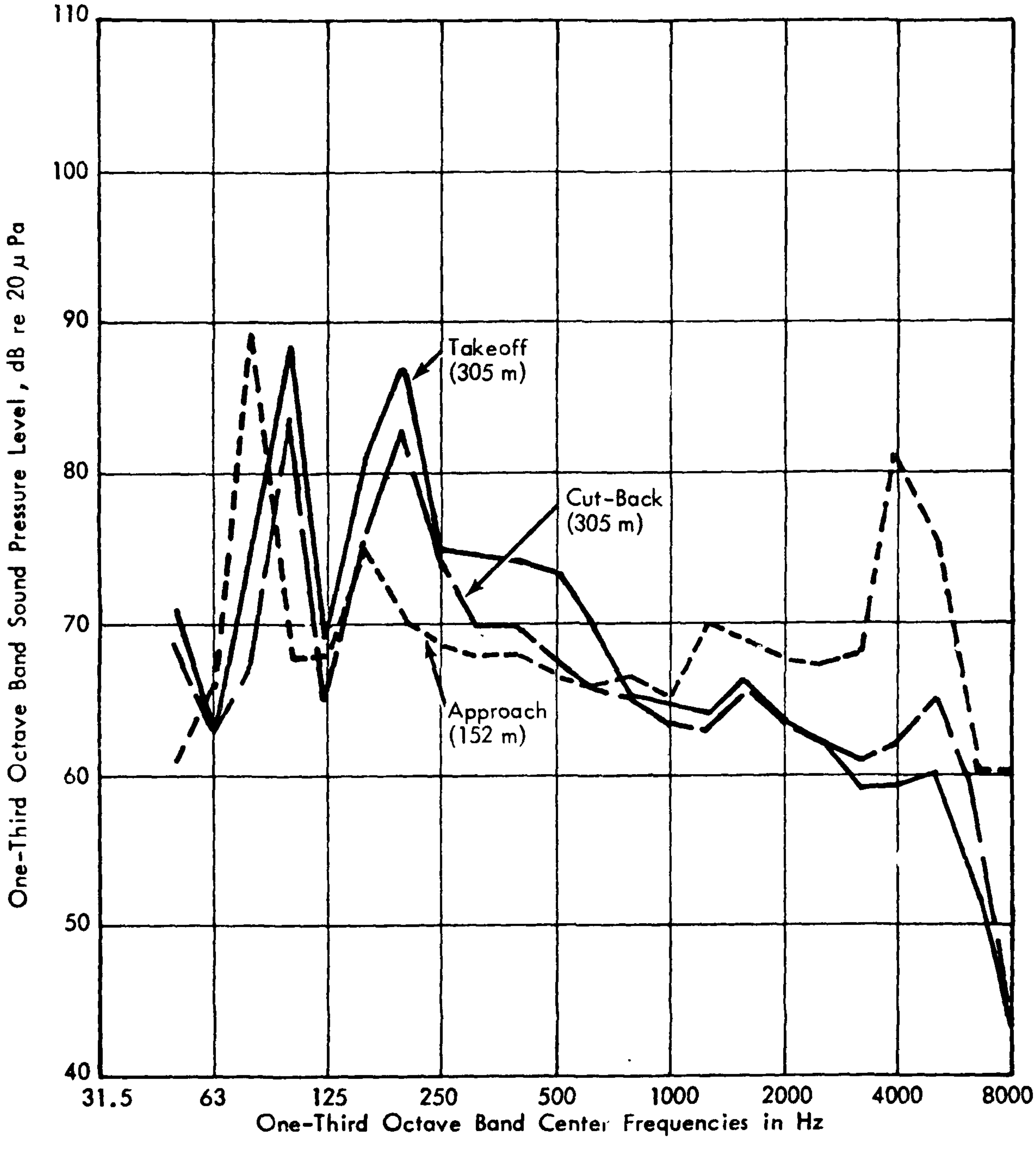


FIGURE 22. BASELINE SPECTRA: AIRPLANE 3

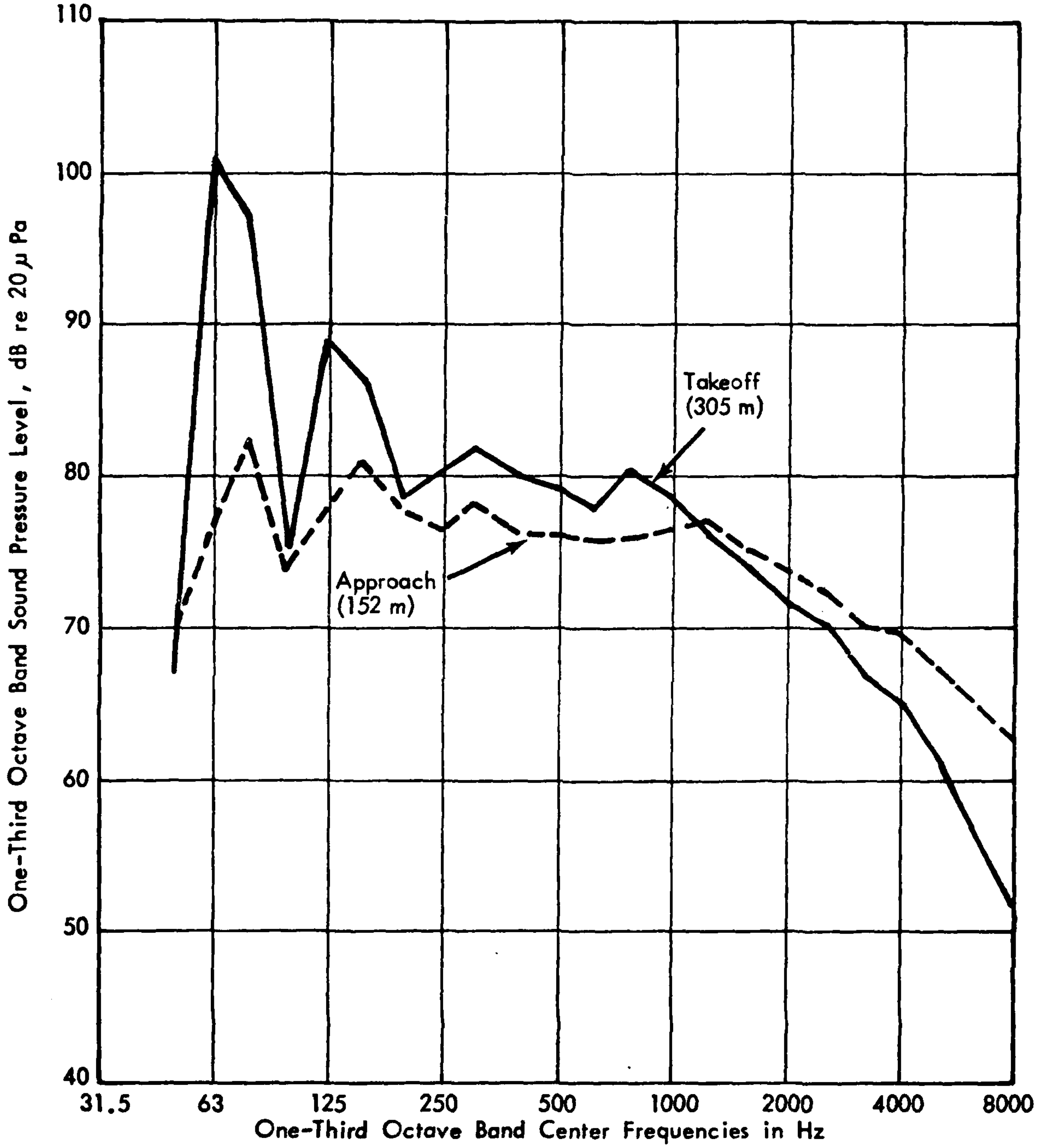


FIGURE 23. BASELINE SPECTRA: AIRPLANE 4

in the engine, although it is often difficult to identify the specific sources.

Broadband engine noise is generated by the flow from the engine exhaust nozzle, as in the case of a turbofan engine, although the acoustic power generated by the exhaust of a turboprop engine is much lower than that of a turbofan engine. The extent to which the exhaust noise is detected by an observer on the ground will depend on the amount of shielding provided by the airplane structure. For example the Lockheed L-382 and Electra aircraft have similar Allison engines but in the first case the exhaust discharges beneath the wing and in the second case, above the wing. Measurements indicate that the below-the-wing discharge results in higher noise levels in the frequency range of 250 to 1000 Hz, approximately.

5.3 Noise Control Approaches

Having defined the baseline spectra for the study aircraft, noise control methods were applied separately to the propeller and engine. Propeller noise was reduced at source but, because of the long lead times involved with engine development and certification, engine noise control was applied only to the propagation path. Noise control methods were considered in general terms since precise details of the propellers and engines could not be defined.

The review in Section 4 indicates that the largest reductions in propeller noise are associated with changes to propeller rpm and diameter, number of blades, and blade thickness. Estimates of the noise reductions likely to be achieved in practice were obtained using Eq. (12) as a basis. The procedure was supplemented,

as appropriate, by inputs from the SAE procedure [18], Hanson's analysis [1], and the results of Succi [11] and Klatte and Metzger [20]. This multi-element approach was chosen in order to take into account the different assumptions associated with the different methods. Effects of airfoil shape and blade loading were included implicitly because it was assumed that propeller efficiency remained unchanged and there was no loss of power when rpm, diameter and blade number were changed. Blade sweep, irregular blade spacing, and ducted propellers were excluded. Blade sweep has a negligible influence on the noise from tractor propellers at low Mach numbers; irregular blade spacing and ducted propellers were not considered to be appropriate solutions in the present study.

Noise control methods envisaged for the engine make use of current lining technology developed for turbofan engine inlets and exhausts. This technology has been reviewed in [15]. The geometry of turboprop engines and nacelles will place severe constraints on available space for acoustic linings in inlets and exhausts, so that it is unlikely that large noise reductions can be achieved. However, the required reductions in compressor or turbine noise are not large in most cases. Propagation paths associated with some of the discrete frequency noise components are not well defined and it has been assumed that the installation of nacelle panels with high acoustic transmission losses might be necessary in addition to treatment of the inlet and exhaust ducts. Shielding of the exhausts, achieved by ducting the flow over the wing, or by designing the engine installation initially so that the exhaust duct is above the wing, could also be used as a noise control design feature.

Noise control methods applied to the four study airplanes are

presented in the remainder of this section, and the resulting reductions in airplane noise are described in Sections 5.4 and 5.5.

Airplane 1

The baseline airplane has a propeller rpm of 2200 at takeoff and 1700 at approach. The propeller has three blades and a diameter of 2.18 m (7.2 ft) which is obtained by cutting back a basic propeller with a 2.57 m (8.4 ft) diameter. Thus the tip will be relatively thick.

As a noise control measure, the propeller rpm for takeoff was reduced to 2000 and then to 1700, with the value for approach being maintained at 1700. The modified rpm values were selected as being compatible with current PT6A technology, the 2000 rpm value being associated with the -41 model and 1700 rpm with the -45A. Both the -41 and -45A models generate higher engine power than is required for Airplane 1. A constant rpm value of 1700 was selected for approach condition to be consistent with current operating procedures for the PT6A-45A on, for example, the Mohawk 298. The gear ratios required for the reduced rpm conditions are the same as those in current use on PT6A engines.

Propeller diameter remains unchanged at 2.18 m, so that the tip helical Mach number at takeoff is reduced from a baseline value of 0.75 to 0.69 and then to 0.59. This is a total reduction of about 21.5%. It is assumed that the propeller thrust is unchanged, which means that modifications have to be made to blade shape to increase propeller efficiency at low speeds. Current improvements in blade technology should be able to provide this increase in efficiency.

A blade increase from 3 to 4 is proposed as an additional noise control feature. Assuming that propeller thrust and blade lift coefficient are maintained constant, the blade solidity can be kept constant and blade chord reduced. Since the baseline propeller has a relatively thick tip, a reduction in tip thickness is possible as a noise control method. The reduction in thickness is taken to be 30% relative to the baseline value. This is a typical value for present day blade designs.

Although compressor tones make only a small contribution to the baseline noise spectra, the use of inlet treatments was investigated. A small amount of sound-absorbing lining was assumed installed on the walls of the inlet duct and plenum, the acoustic absorption requirements also being small. Additional reduction of engine noise is postulated by the provision of a muffler for the exhaust.

Airplane 2

This airplane utilizes new engine technology and the engine/propeller combination thus has low noise features in the baseline design. The propeller has four blades with thin tips and operates at low rpm and low tip Mach number. Therefore, the potential for further noise reductions is not large.

The main noise control approach applied to Airplane 2 is that of reducing propeller rpm to even lower values, from a baseline of 1300 to 1100 and then to 1000. With propeller diameter being maintained at 3.20 m (10.5 ft), the tip helical Mach number was reduced from the baseline value of 0.67 to 0.57 and

then to 0.53, a total reduction of about 21%. In making these reductions it was assumed that propeller thrust remained constant. This implies that it would be necessary to make changes to blade airfoil section and planform in order to increase propeller efficiency at low speeeds. However, such changes should be feasible with current technology advances.

A small amount of inlet treatment is proposed to reduce inlet noise. Also exhaust noise reduction is postulated by directing the exhaust to an over-the-wing location.

Airplane 3

The Dart engine makes a significant contribution to the propulsion system noise levels. Thus an important part of the noise control approach is the reduction of engine noise, particularly compressor noise.

The baseline airplane has a propeller rpm of 1400 at takeoff, 1350 at cutback, and 1125 at approach. The propeller has a 120 foot diameter, so that the tip helical Mach numbers are 0.81, 0.78 and 0.66, respectively for the three conditions. Two reductions to propeller rpm are considered for noise control purposes, resulting in take-off values of 1300 and 1100, respectively. These are associated with gear ratios of 0.086:1 and 0.073:1, as compared to a baseline value of 0.093:1. These increased gear ratios are associated with current Dart developments since the Dart Mark 542 has a gear ratio of 0.0775:1. The changes in gear ratio also result in corresponding reductions in propeller rpm at cutback and approach conditions. As for Airplanes 1 and 2, the reductions in rpm have to be accompanied by changes to the propeller

in order to maintain thrust (and increase propeller efficiency) at low speeds.

Since the baseline propeller operates at a fairly high tip Mach number, it was considered worthwhile to allow some modification to tip shape as a possible noise control approach. The tip was assumed to have a more elliptical planform, with some other changes to propeller shape perhaps being necessary in order to maintain net thrust.

Compressor noise levels are reduced by the insertion of sound absorbing linings in the annular inlet to the engine. The treatment will be placed on both walls of the inlet and a small extension to the inlet tip will be necessary. The linings are assumed to be tuned to the compressor blade passage frequency for the approach condition but the attenuation bandwidth will be sufficiently wide to provide significant noise reduction at take-off rpm. Two insertion loss characteristics are assumed for the lining, in one case the maximum attenuation being 10 dB and in the other 15 dB.

Other engine noise components are observed in the baseline spectra and it is believed that some are radiated by the gears. Thus additional engine noise control treatments are postulated to reduce the engine noise radiated through the engine nacelle casing. This will be achieved by the use of nacelle covers with increased transmission loss.

<u>Airplane 4</u>

The baseline airplane is assumed to have a 14-foot diameter propeller which operates at a constant speed of 1020 rpm.

The propeller has four blades and the tip helical Mach number for takeoff and approach is 0.69. Proposed noise reduction methods include a 10% reduction in engine rpm to 920, with a corresponding reduction in tip helical Mach number from 0.69 to 0.63. In addition as a major change, the number of blades was increased from 4 to 8 with constant propeller diameter and solidity. Then the propeller diameter was reduced by 10% to 12.6 ft. As the baseline propellers have squared-off tips, some modification to elliptical planform was considered. These changes in propeller rpm diameter and number of blades imply, as in previous cases, that modifications have to be made to blade shape and loading in order to maintain the same net thrust for all configurations.

Engine noise control is introduced in the form of sound absorbing linings in the inlet and reduction of exhaust noise. In the latter case it is desirable that the exhaust be ducted to an over-the-wing location in order to provide shielding. Alternatively, the engine installation can be chosen, as on the Lockheed Electra, to provide over-the-wing discharge for the exhaust.

5.4 Measures of Noise Benefits

5.4.1 Effective Perceived Noise Levels For FAR Part 36 Conditions

Comparison of sound levels at FAR Part 36 measurement locations has become a widely used method for describing the noise of airplanes, with changes in sound levels at these points being accepted as a primary measure of the acoustical benefits obtained from the application of noise control technology.

Noise data for each of the three locations used to define the noise limits provides a description of different noise characteristics of an airplane. The basic noise characteristics of the airplane are demonstrated for takeoff power by the sideline measurement and for approach power by the approach measurement. Both of these measurements, in practice, are obtained at essentially constant distances to the airplane, irrespective of performance. Data for the takeoff position are less comparative between aircraft since the effects of airplane performance, e.g., its climb capability, are intermixed with any noise reduction possible through power reduction.

Sound levels are reported under FAR Part 36 conditions for transport category airplanes in terms of effective perceived noise level, EPNL. In this study these values are stated for the Appendix C locations specified in Amendment 9:

Takeoff: 6500 meters from brake release
Sideline: 450 meters perpendicular to the runway centerline
Approach: 2000 meters from runway threshold

An important aspect of the use of EPNL is its frequency weighting which reasonably well rates different sounds in terms of their subjective qualities as judged by human observers. This is particularly important for turboprop airplanes, due to the significantly different frequency ranges in which propeller noise is dominant as compared to engine noise. Reduction of one component of the complete noise signature of an airplane by 10 or 15 decibels may result in only a few decibels reduction in EPNL. The primary measure noise of control benefits in this study is thus the reduction in EPNL at the Appendix C locations, relative to the baseline values.

Airplane 1 of this study would come under the propeller-driven small aircraft provisions of FAR Part 36, Appendix F. This requirement specifies maximum A-weighted sound level as the measure to be used for compliance, obtained during a level flyover at maximum normal rated power, 305 m (1000 ft) above ground. Maximum A-weighted sound level for this test condition, as well as for the same height, but at best rate-of-climb speed, V_y, was computed for the baseline airplane. The incremental changes in sound level produced by the various noise control options at the Appendix C takeoff position can be used as approximate measures of the change in Appendix F levels for the same options.

5.4.2 Area Enclosed by Constant EPNL Contours

As useful as Part 36 noise levels are, they still only specify noise levels at three points around an airport. Another method for describing the noise performance of an airplane is the area encompassed by a constant noise level contour for takeoff and approach operations, or their sum during a straight-in approach, straight-out departure. This kind of information is often useful in assessing the contribution of a particular airplane to the noise environment in populated areas around an airport. Areas enclosed by two constant EPNL contours for takeoff and approach were computed for the baseline case for each of the study airplanes, and the reduced areas obtained from each of the noise control options.

5.5 Results of Noise Control Analyses

Noise reductions for each of the applicable noise control measures, for each of the study airplanes, were applied to

reduce the reference one-third octave sound pressure levels for the appropriate source contributions to the composite spectrum of the airplane. A new composite spectrum was thus derived for the modified installation. A revised EPNL versus distance function was developed for each modification. This function, coupled with the airplane's performance, was used to predict revised EPNL values at the appropriate measurement locations, and to compute revised areas for contours of constant EPNL. The results are listed in Tables 4 to 7.

With the exception of the approach noise control for Airplane 3, and the largest propeller revolution rate reductions for Airplanes 1 and 3, none of the noise control measures, either separately or in combination, provides a noise reduction of more than 5 decibels relative to the baseline airplanes. This is not too surprising, since Airplanes 1 and 2 start from baseline conditions where the EPNL values are from 7 to 13 decibels below the Stage 3 noise limits, Airplane 3 has baseline sound levels that comply with Stage 2 noise limits, and Airplane 4 has baseline sound levels that can comply with the Stage 3 limits if a power cutback is used and tradeoffs are made for the slight exceedance at takeoff and sideline by the margin on approach. Baseline sound levels of the Appendix C locations, and the sound levels that result after the maximum noise reduction considered in this study has been applied, are shown on Figure 24 with a comparison to Stage 3 noise limits.

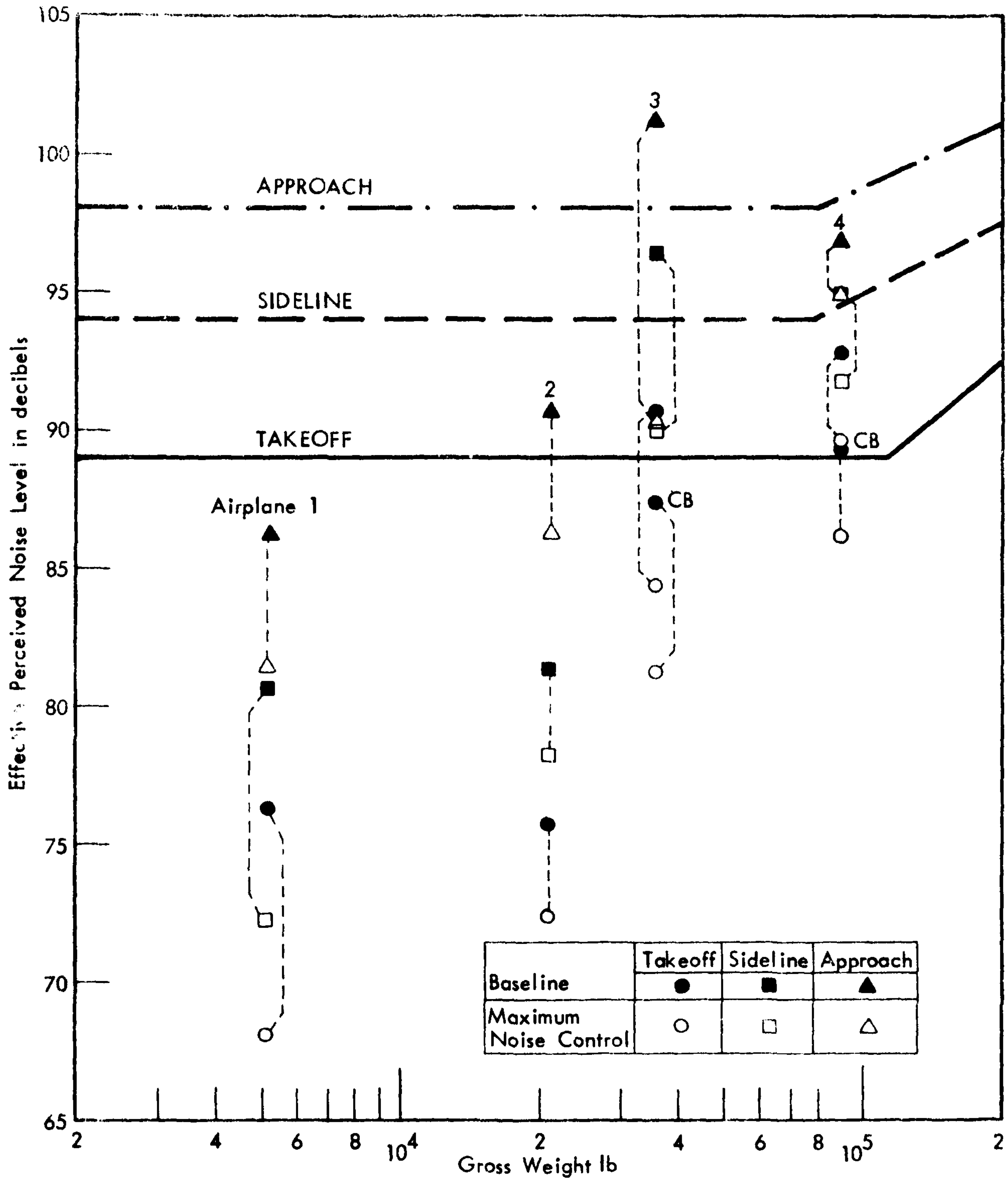


FIGURE 24. STUDY AIRPLANE SOUND LEVELS COMPARED TO FAR 36 STAGE 3 NOISE LIMITS

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NOISE ABATEMENT TECHNOLOGY OPTIONS FOR CONVENTIONAL TURBOPROP A--ETC(U)
JUN 81   W J GALLOWAY, J F WILBY   DOT-FA78WA-4190

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TABLE 4

AIRPLANE 1 - REDUCTION IN SOUND LEVELS AND AREA WITHIN 80 AND 85 EPNL FOR DIFFERENT NOISE CONTROL MEASURES

Case	Inlet Treatment	Thin Prop Tip	2000 rpm	1700 rpm	4 bl. Prop	Inlet & Exhaust Treatment	EPNL Reduction in dB T/O	EPNL Reduction in dB Apch	Area Within 80 EPNL - sq. miles T/O	Area Within 80 EPNL - sq. miles Apch	Area Within 80 EPNL - sq. miles Total	Area Within 85 EPNL - sq. miles T/O	Area Within 85 EPNL - sq. miles Apch	Area Within 85 EPNL - sq. miles Total
Baseline (thick tip)									1.19	1.06	2.25	0.32	0.37	0.69
1	x						-0.1	-2.2	1.15	0.69	1.84	0.31	0.19	0.50
2		x					-0.6	-0.1	1.00	1.03	2.03	0.27	0.36	0.63
3	x	x					-0.7	-2.3	0.98	0.66	1.54	0.26	0.17	0.43
4			x				-1.0	0	0.92	1.06	1.98	0.24	0.37	0.61
5				x			-5.1	0	0.31	1.06	1.36	0.08	0.37	0.45
6				x	x		-6.2	0	0.23	1.06	1.29	0.06	0.37	0.43
7		x		x	x		-6.8	-0.1	0.15	1.03	1.18	0.06	0.36	0.41
8	x	x		x	x		-6.9	-2.3	0.15	0.66	0.81	0.05	0.17	0.23
9		x		x	x	x	-8.2	-4.8	0.04	0.38	0.42	0.03	0.03	0.06

EPNL at Appendix C Locations

	Baseline	Stage 3	Margin
Takeoff	76.2	89	12.8
Sideline	80.6	94	13.4
Approach	86.1	98	11.9

Level Flyovers at 1000 ft.

	L_A	L_{EPN}
Takeoff power, 188 knots (Appendix F, without performance adjustment)	76.6	84.8
Takeoff power, 100 knots	70.6	82.6

TABLE 5

AIRPLANE 2 - REDUCTION IN SOUND LEVELS AND AREA WITHIN 80 AND 85 EPNL FOR DIFFERENT NOISE CONTROL MEASURES

Case	Inlet Treatment	Exhaust Treatment	1100 rpm	1000 rpm	EPNL Reduction in dB		Area Within 80 EPNL - sq. miles			Area Within 85 EPNL - sq. miles		
					T/O	Apch	T/O	Apch	Total	T/O	Apch	Total
Baseline							0.87	3.10	3.97	0.46	1.40	1.86
1	x				-0.1	-1.7	0.85	2.32	3.17	0.45	1.07	1.52
2	x	x			-0.7	-3.7	0.80	1.70	2.50	0.42	0.79	1.21
3			x		-1.1	-0.7	0.75	2.75	3.50	0.39	1.25	1.64
4				x	-2.4	-0.7	0.65	2.75	3.40	0.33	1.25	1.58
5	x	x		x	-3.3	-4.4	0.58	1.55	2.13	0.29	0.62	0.91

EPNL at Appendix C Locations

	Baseline	Stage 3	Margin
Takeoff	75.7	89	13.3
Sideline	81.4	94	12.6
Approach	90.7	98	7.3

TABLE 6

AIRPLANE 3 - REDUCTION IN SOUND LEVELS AND AREA WITHIN 85 AND 90 EPNL FOR DIFFERENT NOISE CONTROL MEASURES

Case	10 dB Inlet NR	15 dB Inlet NR	Gear NR	0.086:1 12 ft.	0.073:1 13 ft.	Tip Shape	Prop Air Foil	EPNL Reduction in dB		Area Within 85 EPNL - sq. miles			Area Within 90 EPNL - sq. miles		
								T/O	Apch	T/O	Apch	Total	T/O	Apch	Total
Baseline (0.093:1 12 ft.)										10.05	5.00	15.05	2.80	2.15	4.95
1	x							-0.5	-7.1	9.50	1.41	10.91	2.40	0.38	2.78
2		x						-0.6	-8.9	9.20	1.05	10.25	2.30	0.29	2.59
3			x					-0.9	-0.2	8.70	4.80	13.50	2.20	2.05	4.25
4				x				-3.8	0	4.00	5.00	9.00	0.90	2.15	3.05
5					x			-5.5	-0.3	2.40	4.50	6.90	0.56	2.00	2.56
6						x		-0.8	0	8.80	5.00	13.80	2.25	2.15	4.40
7							x	-0.8	0	8.80	5.00	13.80	2.25	2.15	4.40
8		x	x		x	x	x	-6.3	-10.7	1.85	0.73	2.58	0.44	0.22	0.66

EPNL at Appendix C Locations

	Baseline	Stage 3	Margin	Stage 2	Margin
Takeoff-Max. Power	90.6	89	-1.6	93	2.4
Takeoff-Cutback	87.4	89	1.6	93	5.6
Sideline	96.3	94	-2.3	102	5.7
Approach	101.2	98	-3.2	102	0.8

TABLE 7

AIRPLANE 4 - REDUCTION IN SOUND LEVELS AND AREA WITHIN 85 and 90 EPNL
FOR DIFFERENT NOISE CONTROL MEASURES

Case	Inlet Nr	Exhaust Nr	Reduce rpm	Blade Shape	8 bl. Prop	Reduce dia. 10%	EPNL Reduction in dB T/O	EPNL Reduction in dB Apch	Area Within 85 EPNL - sq. miles T/O	Apch	Total	Area Within 90 EPNL - sq. miles T/O	Apch	Total
Baseline									15.00	5.30	20.30	5.30	1.60	6.90
1	x						0	-0.1	15.00	5.00	20.00	5.30	1.55	6.85
2		x					-1.0	-1.1	12.50	4.20	16.70	4.40	1.20	5.60
3			x				-0.6	-0.5	13.20	4.80	18.00	4.60	1.40	6.00
4				x			-0.4	-0.4	14.00	4.90	18.90	4.90	1.47	6.37
5	x	x	x				-1.8	-1.6	10.07	3.55	13.62	3.45	1.05	4.50
6					x		-0.3	-0.6	14.30	4.60	18.90	5.00	1.35	6.35
7					x	x	-2.0	-0.6	10.02	4.60	14.62	3.30	1.35	4.65
8	x	x			x	x	-3.3	-2.0	7.40	3.40	10.80	2.40	0.97	3.37

EPNL at Appendix C Locations

	Baseline	Stage 3	Margin
Takeoff-max power	92.8	89	-3.8
Takeoff-cut back	89.3	89	-0.3
Sideline	94.9	94.6	-0.3
Approach	96.8	98.5	1.7

6.0 EFFECT OF NOISE CONTROL MEASURES ON PERFORMANCE AND COST

Noise control measures that add to the empty weight of an airplane or alter its fuel consumption will decrease the utility of an airplane and add to its costs. The effect of noise control measures that replace existing components without increasing weight or decreasing performance add only to acquisition price, if there is any additional cost.

None of the noise control measures considered in this study is assumed to increase fuel consumption or decrease engine performance. A number of the measures call for lower propeller rotational speeds, which in turn require altered propeller designs with adequate advance ratios to maintain satisfactory climb performance. Since conventional propeller designs that operate at these rotational speeds and provide satisfactory climb and cruise efficiencies are currently in service, it is assumed that conventional technology can be employed so that climb and cruise performance will not be degraded. Where propeller changes have been used as a noise control measure, it has been assumed that no aerodynamic performance improvement over the baseline designs is provided, and that conventional metal construction has been employed, implying weight increases in some cases. These last two assumptions are conservative in that research to date shows that improved blade efficiencies have been demonstrated over a wide range of rotational speeds, and that the use of composite materials such as Kevlar and fiberglass reduce propeller weight substantially, as compared to conventional designs.

While no changes in engine performance or fuel consumption are associated with the noise control measures, most do involve an increase in empty weight of the airplane, however small the increase might be. In a practical sense, since none of the weight increments exceeds one percent of the aircraft gross weight, a manufacturer would probably simply certify the aircraft at this slightly higher weight. However, to obtain some assessment of costs for use in this study it is assumed that weight increases due to noise control cause an incremental increase in direct operating cost (DOC), which is a function of airplane weight.

6.1 Incremental Weight Increase For Different Noise Control Measures

Increments in weight, over the baseline airplane weights, for each of the noise control measures considered in Section 5 have been estimated in a number of ways. Changes in propeller weights were estimated by comparison with different versions of existing propellers where possible. Where no direct comparison was available the weight prediction procedure of Ref. 20 was used. Weights for inlet and exhaust treatments were estimated by the methods in Ref. 15, scaled appropriately for engine size. Weights associated with engine-propeller gear ratio changes were estimated by comparing different gear ratio versions of existing engines and by information obtained in discussion with engine manufacturers. The incremental increases in weight per airplane for each noise control measure requiring a weight increase are listed in Table 8.

TABLE 8

INCREMENTAL WEIGHT AND ACQUISITION COST ESTIMATES FOR NOISE CONTROL MEASURES

	Δ Weight kg (lb)	Δ Cost 1980 dollars
AIRPLANE 1		
Reduce to 1700 rpm	6.8 (15)	0
4 blade propeller	4.6 (10)	2,000
Inlet treatment	2.3 (5)	1,500
Exhaust treatment	4.6 (10)	1,000
AIRPLANE 2		
Reduce to 1100 rpm	52.6 (116)	5,000
Reduce to 1000 rpm	84.4 (186)	10,000
Inlet treatment	9.1 (20)	8,000
Exhaust duct	9.1 (20)	1,000
AIRPLANE 3		
Gear ratio 0.086:1	30.C (66)	10,000
Gear ratio 0.073:1	86.2(190)	20,000
Inlet treatment - 10 dB	13.6 (30)	17,000
Inlet treatment - 15 dB	27.2 (60)	21,000
Nacelle treatment for gear noise	34.8 (80)	4,000
AIRPLANE 4		
Reduce to 920 rpm	36.2 (80)	25,000
Inlet treatment	13.6 (30)	17,000
8 blade propeller	108.6(240)	37,000

6.2 Acquisition Costs For Noise Control Measures

Increases in airplane acquisition cost have been estimated for each of the noise control measures. Development and certification costs are assumed to be amortized over 200 airplanes and are included in the acquisition cost. Propeller costs were estimated by comparison to existing (1980) prices where possible, or by the cost estimating procedure of Ref. 20 where necessary. Inlet and exhaust treatment costs were estimated by scaling costs of existing treatments for engine size and treatment weight. It was assumed that re-ducting the exhaust over the wing for Airplane 4 would be part of the initial design at no increase in cost. Costs for changing gear ratios in some instances do not require new gear boxes and are essentially zero. In other instances costs were estimated in terms of incremental weight increases over the existing gear box weights. The incremental acquisition costs associated with each noise control measure are listed in Table 8.

6.3 Change in Direct Operating Costs

Although most of the incremental weight increases assumed for the different noise control measures are small, they are treated here as effectively increasing the basic operating weight of Airplanes 2, 3, and 4, causing an increase in DOC.

Direct operating costs for Airplanes 2, 3, and 4 were estimated from analyses of data for existing turboprop airplanes in commuter airline service [36]. The airplanes used in the analyses were the deHavilland DHC-6, Embraer 110PJ, Swearingen SA226-TC, Shorts SD3-30, deHavilland DHC-7, Fokker F27MK500, and British Aerospace HS748-2B. A number of airplane variables were

examined to derive a simple relationship between airplane performance parameters and DOC. Although substantial differences exist in such variables as airplane size, acquisition cost, fuel consumption (at $1.25 per gallon), cruise speed, block speed, payload/range tradeoffs, maintenance cost, and crew cost, DOC in dollars per hour can be expressed, for the sample airplanes, in terms of cruise speed in knots, V_c, and number of passenger seats, N. For airplanes with retractable gear this expression is:

$$DOC = \frac{V_c \times N}{1.38} (0.1470 - 2.33 \times 10^{-4} V_c)$$

For airplanes with fixed gear the constant 1.38 is replaced by 1.26. These expressions predict the hourly DOC for the seven airplanes within 1.4 percent or less, except for the SA226-TC which is underpredicted by 17 percent, and the Embraer 110P1 which is underpredicted by 9 percent.

The DOC in dollars per block hour derived in this manner for the study airplanes are:

Airplane	DOC - dollars per block hour
2	470
3	536
4	1697

In this calculation, Airplane 4 was assumed to have an equivalent passenger configuration of 100 seats, based on an average ratio of number of seats to gross weight of 1.1×10^{-3}.

An increase in airplane basic operating weight (empty weight,

plus crew and cabin supplied) produced by the addition of noise control measures will cause an increase in DOC. Data from the seven turboprops listed above show an average direct operating cost in dollar per hour of 0.033 per pound, with a standard deviation of 0.005. Despite the range of airplane weights involved (operating weights from 7,700 to 28,000 pounds, corresponding to maximum takeoff weights of 12,500 to 46,500 pounds) the DOC per hour per pound of operating weight is essentially uncorrelated with airplane weight (linear regression: r^2=0.252). For the purpose of this study it is assumed that each additional pound of weight added by noise control measures increases the DOC per hour by 0.035 dollars.

6.4 Incremental Costs for Noise Control Measures and Related Benefits

The effect of increased acquistion costs for the noise control measures was considered in terms of the incremental increase in net present value (NPV) of the baseline airplanes due to the incremental increase in cost over the depreciation life of the basic airplane. Airplane 1 was assumed to be depreciated over 7 years to a 20 percent residual value. Airplanes 2, 3, and 4 were assumed to have 12 year depreciation to a 15 percent residual value, typical of airplanes in commuter airline use. A discount rate of 10 percent was used in calculating NPV. The acquisition cost for the different noise control measures applied to the four study airplanes are summarized in terms of NPV in 1980 dollars in Tables 9, 10, 11 and 12.

The increases in DOC for Airplanes 2, 3, and 4 for the various noise control measures, are also shown in Tables 10, 11, and 12. The data are listed in both increases in DOC in dollars per hour

and in the percentage of DOC these amounts represent. The areas enclosed by a constant value of EPNL for the different noise control measures listed in Tables 4 to 7 can be matched to the incremental costs associated with these measures to obtain a measure of the improvement in noise reduction for different costs. These data are also listed in Tables 9, 10, 11 and 12.

TABLE 9

INCREMENTAL NPV OF NOISE CONTROL AND AREA
WITHIN 85 EPNL - AIRPLANE 1

Case	Measure	Capital NPV 1000 dollars	Area - Sq. Miles
Baseline		0	0.69
1	Inlet treatment	0.84	0.50
2	Thin tip prop	0	0.63
3	1 + 2	0.84	0.43
4	2000 rpm prop	0	0.61
5	1700 rpm prop	0	0.45
6	4 bl.prop, 1700 rpm	1.12	0.43
7	2 + 6	1.12	0.41
8	1 + 2 + 6	1.96	0.23
9	1 + 2 + 6 + exhaust treatment	2.52	0.06

TABLE 10

INCREMENTAL NPV OF NOISE CONTROL AND AREA
WITHIN 85 EPNL - AIRPLANE 2

Case	Measure	Capital NPV 1000 dollars	Δ DOC dollars per hour	Δ DOC percent	Area - Sq.Miles
Baseline		0	0	0	1.86
1	Inlet treatment	4.16	0.67	0.14	1.52
2	Inlet and exhaust treatment	4.68	1.34	0.28	1.21
3	1100 rpm prop	2.60	3.89	0.83	1.64
4	1000 rpm prop	5.25	6.23	1.33	1.58
5	2 + 4	9.93	7.57	1.61	0.91

DOC: 470 dollars per block hour

TABLE 11

INCREMENTAL NPV OF NOISE CONTROL AND
AREA WITHIN 85 EPNL - AIRPLANE 3

Case		Capital NPV 1000 dollars	Δ DOC dollars per hour	Δ DOC percent	Area - Sq.Miles
Baseline		0	0	0	15.05
1	Inlet treatment - 10 dB	5.61	1.01	0.19	10.91
2	Inlet treatment - 15 dB	6.93	2.01	0.38	10.25
3	Nacelle treatment for gear noise	1.32	2.68	0.50	13.50
4	0.086:1 Gear Ratio - - 12 ft. diam. prop	3.33	2.21	0.41	9.00
5	0.073:1 Gear Ratio - 13 ft. deam. prop	6.66	6.37	1.19	6.90
6	Tip Shape	0	0	0	13.80
7	Improved prop airfoil	0	0	0	13.80
8	2 + 3 + 5 + 6 + 7	14.91	11.06	2.06	2.58

DOC: 536 dollars per block hour

TABLE 12

INCREMENTAL NPV OF NOISE CONTROL AND
AREA WITHIN 85 EPNL - AIRPLANE 4

Case	Measure	Capital NPV 1000 dollars	Δ DOC dollars per hour	Δ DOC percent	Area - Sq.Miles
Baseline		0	0	0	20.3
1	Inlet treatment	5.61	1.01	0.06	20.0
2	Exhaust duct	0	0	0	16.7
3	Reduced prop rpm	8.25	2.68	0.16	18.0
4	Blade shape	0	0	0	18.9
5	1 + 2 _ 3	13.86	3.69	0.22	13.6
6	8 blade prop	12.21	8.04	0.47	18.9
7	6 + 10% diam. reduction	12.21	8.04	0.47	14.6
8	1 + 2 + 7	17.82	9.05	0.53	10.8

DOC: 1697 dollars per block hour

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